3 Methodology of the Analysis of Material Fluxes

With respect to the metabolism of the anthroposphere, the main objective for the investigation of the material balances of processes is to establish flux diagrams for individual elements in regions. In order to reach this goal, methods to analyze material fluxes through single processes as well as through complex combinations of processes and through entire regional anthropospheres have to be developed. In this chapter, such methods are discussed and illustrated by examples of selected processes which are instrumental to important anthropogenic material fluxes.

The development of a scheme for regional material flux starts with a system analysis:

— Which goods and processes are to be included?
— Where are the boundaries of the system?
— Which time span is to be covered?

The first step of this system analysis is to list goods and processes; the next step is to link the goods and processes. The following terminology may be used: each process has input and output goods, and goods have one (or more) origin and destination (Fig. 3.1).

For larger systems, in the analysis of the input/output it is convenient to link goods and processes.

The concept of measuring material balances is not new and has been practiced by engineers for many years (Berthouex and Rudd 1977; Ayres et al. 1985, 1987). In most investigations, the emphasis is placed on the qualities and quantities of certain educts and products which are important from an engineering and/or economical point of view. In order to analyze a process as a part of the metabolism of the anthroposphere, these priorities have to be supplemented by an interest in the *total* material and energy flux of a process.

One of the most important properties of a material is its mass. According to the laws of the conservation of matter, the mass balance of a process can be described by the following equation:

$$S\,A_i = S\,B_j,$$

where

A_i are educts used in the process; B_j are products and waste materials produced in the process.

If the energy is to be included, the following equation is established:

$$S\,A_i + S\,C_k = S\,B_i + S\,D_l,$$

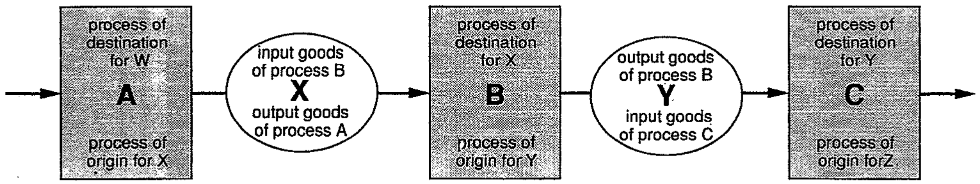

Fig. 3.1. Input and output goods of processes; origin and destination of goods

where

C_k denotes the energy in the educts and energy consumed by the process; D_l is the energy in the products and energy produced by the process.

Educts, products and energy can be present in various forms: the materials in a solid, liquid and gaseous state, the energy as chemical, thermal, electrical or any other form of energy. Therefore, it is sometimes necessary to measure either the mass or the volume (gases) of the educts and products of a process, and to measure, e.g., the temperature, moisture and mass or volume of the educts and products in order to establish an energy balance.

An important property of a process is its kinetics: there are very rapid processes (e.g. the transformation of natural gas to CO_2 and water during combustion takes place in seconds) as well as very slow processes (the transformation of biomass in a landfill to CO_2 and water takes hundreds of years). There is a time lag between inputs and outputs for slow processes (cf. Fig. 2.4); as a consequence, a material balance of a slow process has to take into account that it might not be possible to determine the material balance of such a process at one time. Assessment of the long-term behavior of such processes based on chemodynamic principles might be necessary as well as the investigation of inputs and outputs of several identical processes which are in different time stages: for example, the first stage of the process "sewage sludge reactor landfill" can be described by an investigation of several landfills of different ages from 1 to 30 years; the following long-term behavior may be assessed by the comparison with a peat deposit, a natural analog to a sludge landfill (Lichtensteiger et al. 1989).

3.1 Material Balances of Processes

The term "process" as used in this chapter denotes the transformation, transport or storage of goods. "Transportation" is included as a process because it requires energy and involves other goods and materials (electricity, fuel oil, air, steel, etc.). Also, while in most cases transportation does not change the chemical composition of goods, it sometimes alters the physical characteristics (e.g. density of MSW, rheology of sludges). The same applies to storage. Here, the energy and materials invested in the storage facilities have to be taken into account, too. An important problem of long-term storage (more than 100 years) is the slow transformation by microorganisms and/or geological processes which cannot be followed by experiments or analyses. The mass balance of such a process may require the comparison with other means of storage of known material fluxes, e.g. the long-term process "storage of sewage sludge in a landfill" may be assessed by investigating the genesis of natural peat deposits (Lichtensteiger et al. 1989).

3.1.1 Transformations

Of the three types of processes, the *transformation* of goods is the most important if material balances are to be examined. Through transformation, goods are changed into new products of new qualities and usually new chemical compositions. The chemical composition is given by the stochiometric ratio of the individual elements and the chemical speciation of the elements. The term "material balance" as used in this chapter refers to the balancing of elements for a given process on a mass and/or molar base. While the latter is the more appropriate approach to understand the mechanisms of a process, the balancing on a mass base does not depend on the definition of 1 mol of goods X. It is difficult to define 1 mol of sewage sludge, municipal solid waste or even milk. Therefore, for most purposes, the balance of a process on a mass base (in g) is quite appropriate.

Because of the costs of analysis, in most cases it will not be possible to give a complete balance for all elements involved in the process. This is especially true if rare trace elements are involved in the transformation. Thus, certain indicator elements have to be selected and used as described in Section 2.2. Nevertheless, it might be adequate to select additional elements for a particular mass balance, or to exclude certain selected elements.

A material flux analysis consists of the following:

1. A systems analysis comprising a list of educts (goods) and products.
2. The measurement of the mass fluxes of all educts and products per unit of time for several time periods [mass (for gases: volume) per time or per mass unit of product].
3. The determination of the concentrations of the selected elements in the educts and products for several time periods (mass/mass, or mass/volume).
4. The calculation of the elemental mass fluxes from the fluxes of goods (2) and the measurement of the concentrations of the elements (3).
5. The appropriate presentation of the results.

The process itself can be viewed as a black box. If necessary, e.g. if it is expected that the transformation is dependent on the changes in the qualities of the educts, the process has to be investigated in more detail (cf. the example given in Fig. 3.2).

The results of the mass balance determination is best expressed by transfer coefficients (Fig. 3.3). These coefficients describe for each element the partitioning between the various products of a process.

There are several possibilities to determine the material balance of a process. The most comprehensive and also most costly method is the measurement of all input and output materials of a process during a representative operating time in the field.

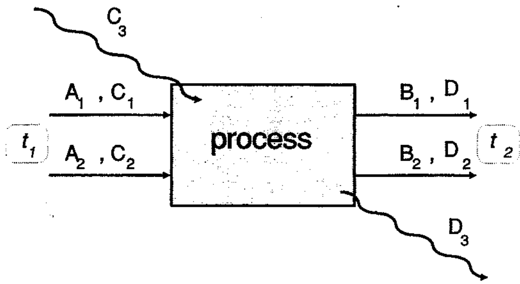

Fig. 3.2. Example of a material and energy balance of a process. The determination of a material balance has to take into account that for slow processes there may be a large time lag (t_2-t_1) between inputs and outputs and that they cannot be measured at the same time. A_1, A_2, C_1, C_2 Educts; B_1, B_2, D_1, D_2 products; C_3 energy input; D_3 energy output

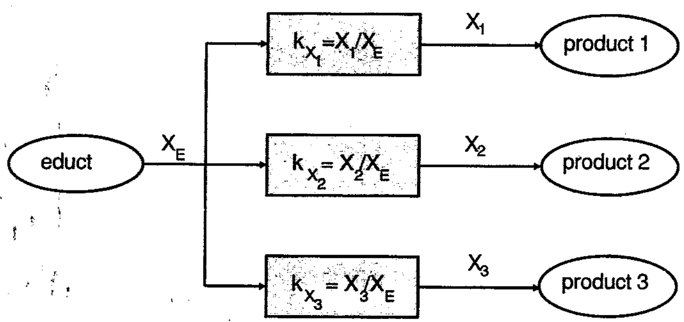

Fig. 3.3. The partitioning of an element X in a process between the products 1, 2 and 3. The transfer coefficients k_x are defined as $X_{product}/X_{educt}$. X is usually given as a flux value (mass per time). The sum of all k_{xi} equals 1

A second method depends also on field measurements, but does not include a complete material balance: only the easily accessible materials are measured, and this result is used to calculate the missing products or educts in the material balance. This method allows one to determine material balances of processes which cannot be investigated by the complete field measurement method. For instance, it will not be possible to directly analyze the input in most waste treatment processes by sampling the waste input, since this material is much too heterogeneous for a cost-efficient sampling and analysis. A third method is based on the utilization of existing information on processes and material fluxes, and combines such existing information to derive material balances of newly investigated processes. This method takes into account that materials flow through an entire chain of processes, starting with ore exploitation, refinement of raw materials, production of consumer products, and discharge of waste materials. Along this chain, much information is available for many processes and material fluxes. In some cases, this information is sufficient to describe the material flux through a new or yet uninvestigated process.

Analysis of Material Fluxes Based on Available Information Only

The simplest, most efficient and inexpensive material balance analysis can be achieved if available information on a process is combined to give the complete flux

of one or more elements through this process. In the following, the flux of chlorine through the process household is investigated in order to determine the concentration of chlorine in the municipal solid waste (Brunner and Ernst 1986). This example illustrates that a material balance of a process (household) may be used also to determine the composition of goods (MSW) which otherwise could not easily be analyzed. Also, it exemplifies that a "process" can be a complex activity like a household, where one to several "average" persons use (transform, transport or store) goods in an "average" way.

The main sources of chlorine in MSW are assumed to be polyvinyl chloride (PVC) and sodium chloride (table salt, NaCl). Minor amounts of Cl are contained in plant materials, paper and other products. Thus, the content of Cl in MSW can be roughly estimated according to the figures on consumption of PVC and NaCl and by assuming the fate of these products during and after consumption. For this example, it is assumed that since sodium chloride is utilized mainly for dietary purposes, 10% of the NaCl consumed is discarded. For PVC, it was estimated that 50 ± 20% is contained in long-living products and the rest is used for low residence time packaging material and consumer goods. There is not yet a steady state for the PVC flux through the anthroposphere. There is a large annual growth rate on the input side and because of the partially long residence time of PVC products, this material accumulates in the human environment. Therefore, the amount of PVC-derived chlorine in MSW has been calculated according to varying percentages of PVC. Despite the fact that Table 3.1 is based on several assumptions, the order of magnitude (5-10 g Cl kg^{-1} MSW) compares well with values resulting from direct waste analysis of 7 g Cl kg^{-1} MSW.

All figures given in Table 3.1 are based on information which is routinely collected by manufacturers or associations of manufacturers of table salt, polymers

Table 3.1 Simplified chlorine balance of the average Swiss household. Educts: tablesalt (NaCl), polyvinyl chloride (PVC); products: sewage, municipal solid waste (MSW); storage: household (HH)

	NaCl		PVC			
Consumption	5		8			kg/capita and year
Fraction discarded	10		30	50	70	%
Mass stored in HH	0		5.6	4	2.4	kg/capita and year
Mass in sewage	4.5		0	0	0	kg/capita and year
Mass in MSW	0.5		2.4	4	5.6	kg/capita and year
Cl content:	610			580		g/kg NaCl, PVC
mass of Cl in NaCl and PVC discarded in MSW	0.31		1.4	2.3	3.2	kg Cl/capita and year
Contribution to the concentration of Cl in MSW	0.9		3.8	6.3	8.8	g Cl/kg MSW
Total Cl in MSW	5	-	10			g Cl/kg MSW
Direct analysis	3.4	-	4.2			[a]
Analysis of waste treatment products	6.9	+-	1.7			[a]

[a]Brunner and Ernst (1986).

and, in the case of municipal solid waste, by communities. Basically, three factors are not well known: (1) the goods other than salt and PVC which contain Cl and which are involved in the process household; (2) the composition of PVC which, due to the additives such as softeners, stabilizers and pigments can contain considerably less than the theoretical 580 g/kg of chlorine; and (3) the fraction of PVC and salt discarded with household refuse. Because of these uncertainties, the range of Cl in MSW given in Table 3.1 denotes only one order of magnitude. The cross-check with the chlorine content of MSW from other measurements indicates that the order of magnitude derived by this method is correct. It has to be kept in mind that for studies on the material fluxes through the anthroposphere, in many cases this degree of accuracy is sufficient.

The values from Table 3.1 may be used to draw Fig. 3.4, which describes the main contributions of the chlorine flux through the process household.

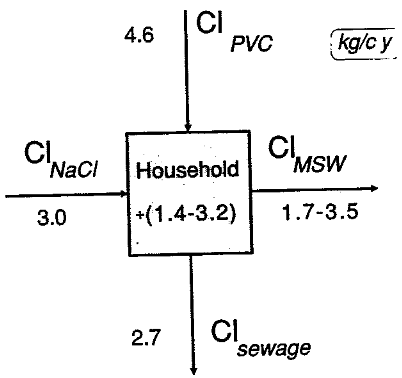

Fig. 3.4. Chlorine balance of the process household. The two inputs (table salt and polyvinyl chloride), which have been taken into account for this balance, are considered to be the most important sources of Cl in a household

The main advantage of the analysis of material balances, applying available information on market products, is the fact that no measurements are needed, and that with little effort good estimations of the element fluxes can be given quickly. Disadvantages of this method include the dependence on the production figures which are usually known on a national level only, and that data are available to a limited amount of goods, processes and elements only.