

**INDICATORS FOR INTEGRATED SUBSTANCE CHAIN  
MANAGEMENT**  
AS A MEASURE FOR ENVIRONMENTAL QUALITY AND SUSTAINABLE DEVELOPMENT

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## 1. Introduction

### 1.1 Goal and scope

The NWO programme "Accumulation of metals in economic/environmental cycles: mechanisms, risks and possible management strategies" (Udo de Haes et al, 1994) is a cooperation between the environmental science departments of four universities in the Netherlands. The goal of this program is to obtain an insight in the flows and stocks of five heavy metals in the Netherlands and the European Union and in the mechanisms that cause environmental problems related to these heavy metals. A central research tool in this program is Substance Flow Analysis (SFA). A general framework for SFA methodology consists of three elements (Udo de Haes et al., 1997):

- goal and system's definition, wherein the SFA system is specified based on the research questions to be answered in the study
- inventory and modelling, wherein the SFA system is quantified
- interpretation of the results, wherein the SFA outcomes are translated into policy relevant terms.

The first two elements of the framework are elaborated in several publications (Van der Voet et al., 1995a and 1995b; Boelens & Olsthoorn, 1996). The subject of this report is the third element of the framework, the interpretation of the results. By "the results", we mean the quantified overview of flows and stocks, in this case the flows and stocks of five metals (copper, zinc, lead, cadmium and aluminium) as they occur in the economy and the environment of The Netherlands and of the European Union. This overview can be obtained by bookkeeping (for a year in the past), static modelling (for a year in the past or for the steady state situation), or dynamic modelling (for a year in the future). Often, such an overview is too complicated to distill precisely the relevant information. Because there is so much information, there is also the risk for rather coincidental outcomes of these are based on only a few criteria. A further interpretation of the overview data is then required.

Such an interpretation can be made from several angles. In this paper, the interpretation is aimed at the environmental consequences of the flows and stocks by defining a set of indicators. These indicators aim to operationalize the concepts of *environmental quality* and *sustainable development* for substance chains as they occur within a region. In the following, several categories of indicators will be defined and related to these concepts. Subsequently, a number of indicators will be elaborated in more detail. The flows of some of the metals out of the NWO programme in the Netherlands will be used as a case in point.

### 1.2 Sustainability, environmental quality and sustainable development

Sustainability, environmental quality and sustainable development are concepts that are used quite commonly in environmental research and policy. They are used to relate the scientific findings of research to value judgments: when we hear speaking of a "sustainable" scenario we do not know its contents, but we do know that it is a "good" scenario. When it comes down to specifying the particulars, it appears that these concepts are operationalized in many different ways. The concepts therefore are more political than scientific, and must be defined in more detail whenever they are used to evaluate the results of a study. The present paper is an attempt to do just that for SFA studies in general, illustrated by the case of copper in The Netherlands. The issue then is, how to interpret the results of an SFA study (the overview of flows and stocks for a given year in a given region) in terms of sustainability, environmental quality and sustainable development. Below, we will specify what we mean by those terms.

Environmental quality is related to the state of the environment and the changes therein. Environmental quality is, according to our definition, sustainable when the various functions required from the environment are not impaired, nor will be in the future. These functions can be divided in a number of categories, such as production functions, regulation functions, carrier functions, and information functions (Van der Maarel & Dauvellier, 1978). Next to that, the "intrinsic value" of nature may be included.

Sustainable development on the other hand refers to human activity, and therewith to the state and changes therein of the societal subsystem. Human activity (development), again by our definition, is sustainable when it does not impair environmental quality as defined above, now or in the future. Thus, environmental quality and sustainable development are related, and for both, a sustainable level may be defined.

It is not easy to operationalize these concepts, not even with a limited scope such as the materials regime of a region. In the first place, the functions required from the environment themselves are not unambiguous. Moreover, the required functions change through time as technology develops and the de-linking of the societal and environmental subsystems progresses (Factor 10 club, 1994; Bringezu, 1993; Van der Voet et al., 1996). In the second place, different functions may have different requirements from the environment(al quality). It will be difficult to deal with these differences when defining these concepts on a generic level, such as required for environmental policy. In the third place, the translation from environmental quality to sustainable development and vice versa leaves space for debate since knowledge regarding the various chains of impact may be incomplete. Moreover, such a translation is not merely a technical issue, but highly depends on choices and societal values.

When related to substance flows, environmental quality is often interpreted as the definition of general concentration limits in the environmental compartments. Although such an interpretation is a valuable start especially for policy makers on the national level, it implies a narrowing down of the concept of environmental quality since the different demands of the different functions as well as the distribution characteristics of the different environmental compartments, in general and for specific locations, are not taken into account. For sustainable development on the other hand, the danger exists that it is translated into emission limits only. This, too, implies a loss of meaning. Issues such as the shifting of problems either to the future or to other countries is also important but is not included in a concentration/emission approach. With the indicators proposed below we intend not to limit ourselves to the emissions and environmental concentrations, but to cover more aspects of environmental quality and sustainable development. It must be kept in mind, however, that this concerns an operationalization of sustainable development and environmental quality regarded from the point of view of the substance flows and stocks in a region only. Other aspects, such as economic and social issues, are also major issues but are outside the scope of SFA.

### 1.3 Types of indicators

Indicators play an important role in the interpretation of environmental data for environmental policy. The general idea is, to aggregate the rather large and ungainly lot of data into a limited set of measures relevant for environmental policy. The concept "indicator" is not strictly defined, and in practice many widely different things may serve as indicators. Several attempts have been made towards a classification of indicators. The OECD for example distinguishes, along the chain of causality, *state*, *pressure* and *response* indicators (OECD, 1993). The *state* indicators provide direct information on the state of the environment, mostly referring to ecosystems and the availability of natural resources. The *pressure* indicators comment on the direct (emissions) and indirect (societal) causes "upchain", which therefore may have an early warning function. For example, the "policy performance indicators", developed by Adriaanse (1993) provide measures by

which the development of certain environmental problems can be followed through time. Other examples, referring more to societal causes, are economic indicators such as the GNP (growth) or the population size (growth). The *response* indicators measure societal activities to combat the environmental problems, for example, the number of discarded bottles taken to the bottle bank.

Opschoor & Reijnders (1991) provide another classification. They distinguish *pressure*, *impact* and *sustainability* indicators. The *pressure* indicators provide information regarding societal activities and emissions, the *impact* indicators refer to the environmental changes as a result of these, and are therefore rather similar to the *state* indicators described above. The *sustainability* indicators are not really separate indicators, but are defined as a reference value for the other two types, indicating a "sustainable" level. The *impact* indicators comment on environmental quality, while the *pressure* indicators measure (sustainable) development. The reference for the acceptability of their levels is formed by the *sustainability* indicators.

Still other classifications are possible. Bakkes et al. (1994) provide an overview of the most common ones. In the following sections, we take the classification by Opschoor & Reijnders as a starting point.

The indicators in this article are meant to provide information with regard to the substance's flows and stocks, relevant for environmental policy. In this case, "environmental policy" can be narrowed down to an integrated substance chain management policy. Substance chain indicators must be constructed in such a way that they provide:

- information on the state of the stocks and flows of a substance on a given moment in time
- early warning for future problems
- information on the changes in flows and stocks over time
- information on the influence of policy measures
- information on various types of problem-shifting.

These demands imply the need for the definition of reference values indicating a desired or sustainable level for the indicators, according to the *sustainability* indicators of Opschoor & Reijnders.

In addition, requirements can be defined for the indicators as a group. The indicators as a group must be usable for the evaluation of an overview for a specific year, but also for the evaluation of changes in flows and stocks over the years and modifications therein, for example as induced by environmental policy. Therefore, a comparison between different regimes must also be possible.

The following requirements can be made for a set of indicators:

- the set as a whole must include all relevant aspects of the substance chain and its environmental impacts
- the individual indicators in a set must be as independent from each other as possible
- the set as a whole must contain as few indicators as is compatible with the two prior demands.

It must be kept in mind that the set of indicators presented below is developed for application in the metals' case study. Most of the indicators can be used also for other substances. However, it is likely that other substances with different hazardous qualities and different environmental and economic properties would require additional indicators, while some of the indicators presented in this paper may be irrelevant.

#### 1.4 Indicators for the evaluation of the flows and stocks of heavy metals

For the definition of substance chain indicators, an approach is chosen starting from the defined SFA system, with its two subsystems. Three types of indicators are distinguished:

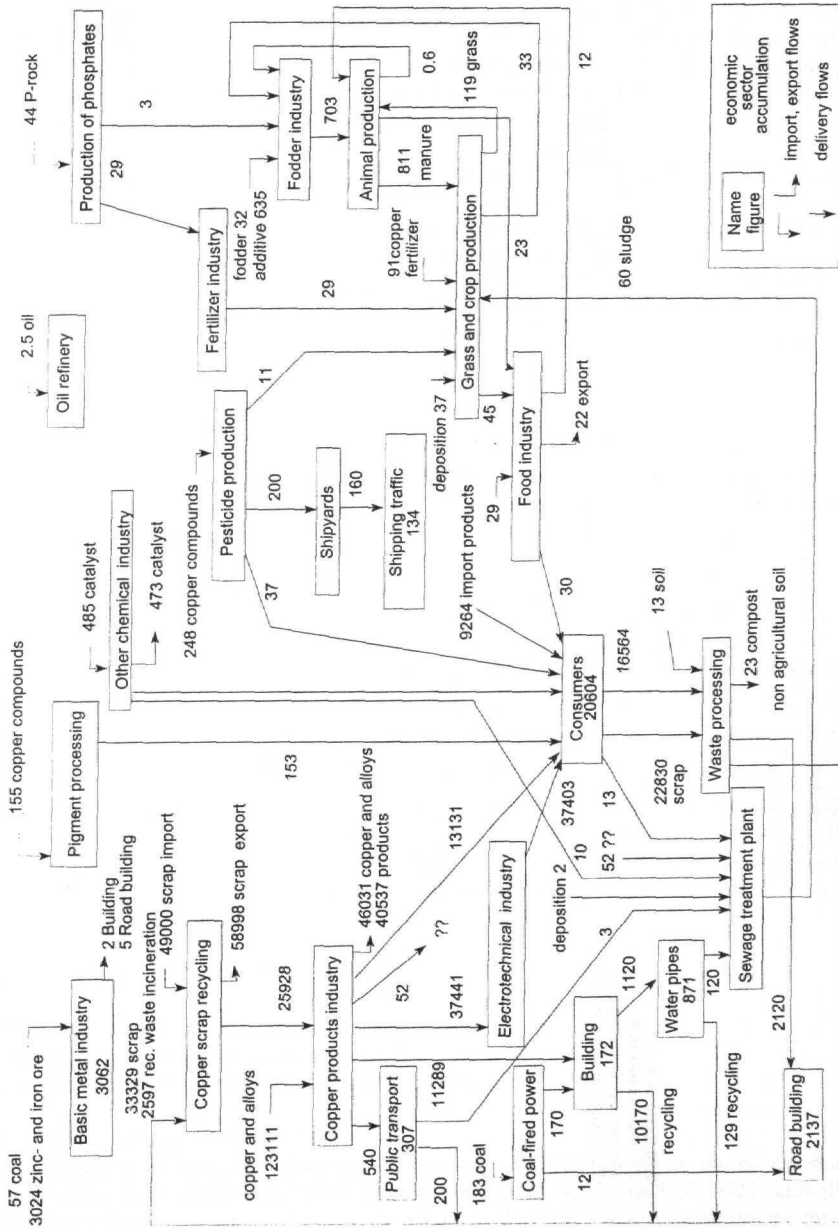
1. indicators concerning the environmental subsystem
2. indicators concerning the economic subsystem
3. indicators concerning the relation of the economic subsystem with the environment and with other systems.

The first type of indicators, containing the *impact* indicators, is most clearly related to the concept of environmental quality. The second type is related to sustainable development. The third type provide the linkage between sustainable development and environmental quality. The second and third types represent the *pressure* indicators: the third refers to the "direct" pressure, while the second type contains indicators that may have an early warning function. For this last type of indicators, defining a reference value or sustainable level will be difficult and sometimes even impossible, as will be shown below. Below, the indicators are defined and for several of them an example is provided out of the heavy metal's case study.

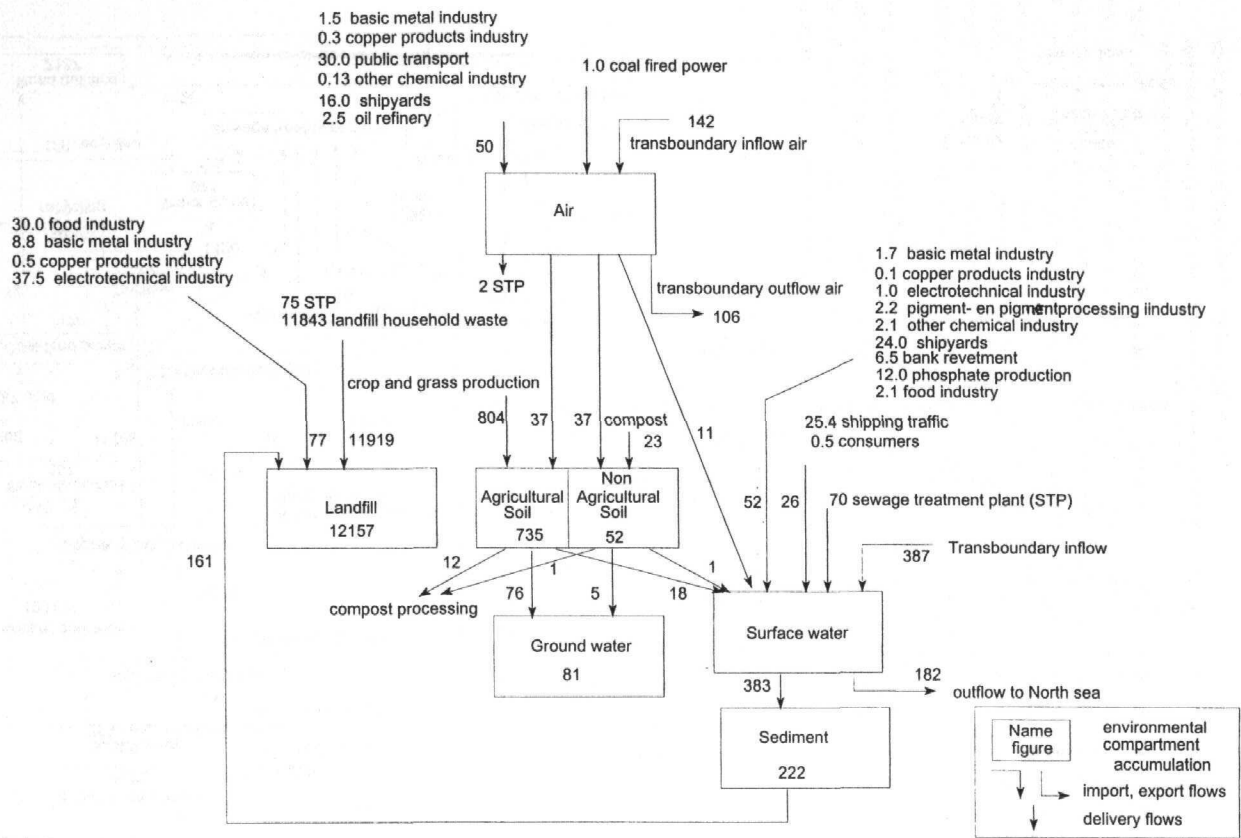
As mentioned above, the flows and stocks of copper in The Netherlands in 1990 will be taken as an example. In Annema et al. (1995) an extensive report of copper flows can be found. Here, the main results of this study is summarized. Figures 1a and 1b provide an overview of the flows of copper in the economy (1a) and the environment (1b).

Figure 1a

The economic flows of copper, The Netherlands, 1990  
(from Annema et al., 1995)



**Figure 1b** The environmental flows of copper, The Netherlands, 1990  
 (from Ammerla et al., 1995)



## 2 Indicators concerning the environmental subsystem

Indicators for flows and stocks in the environmental subsystem are related to pollution, c.q. environmental quality. Not the addition of materials to the environment, but the consequences of such addition for the state of the environment and the changes therein over time is indicated. Therefore, not the environmental flows themselves, but the resulting environmental damage in the sense of health damage, ecosystem deterioration or loss of functions are the key issue. Such information, however, is highly site specific and therefore hardly suitable as a basis for a national or European environmental policy. Therefore, indicators must be defined that are a measure for this damage, without actually pretending to predict whether this damage will occur. Three measures for the risks linked to the environmental flows are proposed here:

1. concentration, i.e. the average concentration of the substance in the environmental compartments within the region
2. daily intake, i.e. the average daily intake of the substance by humans in the region
3. environmental accumulation, i.e. the increase in environmental stocks within the region
4. total emissions, i.e. the total amount of emissions from the economic subsystem into the environment of the region
5. depletion rate, i.e. the contribution of a region to the depletion of global resources

### 2.1 Indicator 1: Concentration

The indicator is the *concentration of a substance in an environmental compartment*. It is a translation of the substance's stock. In addition, a concentration *rise* is a translation of the stock's increase or accumulation (see Ad 3.)

#### *The significance of the indicator*

The calculation of the concentration of a substance in an environmental compartment is a measure for the (potential) loss of environmental quality. It may indicate a human health risk through specific exposure routes, it may indicate a loss of economic functions, for example agriculture or recreation, and it may also indicate a deterioration of the ecosystem. For the several functions or values, separate reference values may be defined.

#### *Method of calculation*

The first step is to select the relevant stock(s) out of the SFA overview, derived from known problems related to the substance in question. The next step, translating stocks into (average) concentrations, involves extra information with regard to the environmental compartments in question (i.e. the mass and/or volume of soil, surface water or others) that the flow or stock is distributed over. The general formula would be

$$c_{s,c} (\text{kg/m}^3) = S_{s,c} (\text{kg}) / V_c (\text{m}^3)$$

with  $c_{s,c}$  the concentration of substance  $s$  in compartment  $c$

$S_{s,c}$  the stock of substance  $s$  in compartment  $c$

and  $V_c$  the volume of the compartment within in area.

#### *Interpretation for environmental policy*

The introduction of reference values in the shape of concentration limits opens opportunities to evaluate flows in an absolute sense. A specific example of this is the PEC/NEC ratio (Predicted Environmental Concentration divided by the No-effect Environmental Concentration), for example as applied in the USES evaluation system for substances (Jager & Visser (eds), 1994). The PEC, a

steady state average concentration for the area, is calculated from emissions with a multimedia model. A PEC/NEC ratio  $> 1$  indicates a risk. The SFA outcome, with the additional data on "amounts of environmental compartment", could be used to calculate a PEC-like value, which can be confronted with a NEC- or NEC-like limit, or another concentration level that has been defined as acceptable.

Introducing concentration limits also opens opportunities to compare different substances. For comparing different PEC/NEC or comparable ratios, the Distance-To-Target (DTT) approach (for example used by Sas (1994)) could be adopted, which in short means: the higher the worse, above a zero-effect value of 1 (actually observed value divided by "sustainable", no-effect, or target value). Two implicit assumptions are made: (1) that the substance's damaging potential has been incorporated in the concentration limit, and (2) that an equal transgression of concentration limits is considered equally "bad" for every substance, independent of the substance's toxic or other environmental damaging potential. Although there are ongoing discussions regarding this approach (Kortman et al., 1994; Anonymous, 1994), the basic idea seems to be suitable.

## 2.2 Indicator 2: Daily intake

The indicator is the *average daily intake of the substance through all different routes by humans*.

### *The significance of the indicator*

The daily intake may serve as an indicator for human health risk.

### *Method of calculation*

With the help of methods of risk assessment, environmental concentrations can be translated into an average daily intake of the substance for humans (for example, Paustenbach 1989). Such methods calculate the intake as a result of the various exposure routes, so that all environmental compartments are included. For other species, the intake may be calculated likewise. The abovementioned USES evaluation system also contains a module to calculate the average daily intake based on a general multimedia environmental model. The actual calculations are not discussed further here.

### *Interpretation for environmental policy*

The human daily intake can be compared with ADI or TDI values, such as defined by the WHO. These values refer to a maximum acceptable intake level, any transgression of these indicates a health risk.

## 2.3 Indicator 3: Environmental accumulation

Environmental accumulation is the increase of a certain stock over the year. It can be defined either on an aggregate (total environmental accumulation) or on a detailed (accumulation in one specific stock) level.

### *The significance of the indicator*

Environmental "sinks", i.e. stocks wherein substances tend to accumulate, are soil, sediment and groundwater. Accumulation may take place as well in the atmosphere, in surface waters and in biota, but the amounts are small as the turnover rate is fast. Accumulation seldom indicates a specific environmental problem. What it does indicate however is the fact that under the current regime the environment is off balance, and that there is a risk for growing environmental problems in the future. If this regime is continued over the years, the environmental stock will continue to

grow and the environmental concentration will rise, eventually transgressing quality standards. Moreover, the outflow out of such a growing stock often tends to increase and lead to problems in other environmental compartments. In the end, the situation will stabilize at a new (possibly undesirable) equilibrium: the long-term steady state situation belonging to a certain materials management regime.

#### *Method of calculation*

This indicator can be extracted directly from the overview of flows and stocks.

#### *Interpretation for environmental policy*

In general, it can be stated that the larger the accumulation is, the more severe is the state of imbalance, and the higher the risk for future problems. As a reference value, a zero accumulation may be adopted: as long as the accumulation continues, the state of imbalance continues. In some cases, a negative accumulation (stock decrease) might even be desirable. However, we may find ourselves entangled in the problem of chemical time bombs (Stigliani & Salomons, 1993): a stock decrease might imply the increasing availability of substances formerly locked safely away in stocks.

The absolute value of the accumulation does not provide much information beyond "less is better". Further elaboration is required to gain more information from the indicator. Three possibilities are presented below:

A first possibility is to relate the accumulation to the size of the stock. The higher *the relative stock increase*, the more severe the state of imbalance and the quicker the concentration limit might be reached.

As a second possibility, a translation can be made from accumulation into a rise in concentration of the substance in the environmental compartment involved, which subsequently can be translated into the *time period (in years) involved in transgressing concentration limits*. In that case, additional information is required: the "amount of environmental compartment" over which the accumulation is spread, the concentration limit for the substance in the compartment, and the starting concentration of the substance in the compartment. For copper in The Netherlands (Annema et al., 1995) the accumulation of 740 tonnes per year of copper in agricultural soil can be translated into an average concentration increase of 2 mg/kg soil per year (with the assumption that the copper accumulates in the top 10 cm of the soil). From a completely clean situation, this would mean a period of almost a century before the Dutch 190 mg/kg limit (Annema et al., 1995) would be transgressed. Since the copper soil stock is already considerable, this period will be much shorter, depending on the local situation.

A third possibility is to calculate the steady state situation belonging to a certain substance regime. In that case, a picture is obtained of the stock's steady state size as a result of the accumulation, if the regime is continued indefinitely. Again, the stock's size *per se* can be used to compare different regimes: the larger the size, the worse the situation. In this option, too, the concentration limit can be introduced for evaluating the consequences of a single regime: the stock's steady state size can be translated into a concentration and then compared with a no-effect level or a policy target level, similar to the *PEC/NEC* approach for toxic substances. If the limit is not transgressed, the accumulation in the present situation can be considered to be no problem. This option is also suitable when comparing the impacts of policy options on the environmental pathways of the substance.

Calculations for the case of copper in The Netherlands show that in the steady state situation resulting from the 1990 regime, the 1990 accumulation can be translated into a steady state stock of 90,000 tonnes of Cu. This would mean an average concentration of 252 mg/kg, and therefore a

transgression of the 190 mg/kg limit. The accumulation of 1990 therefore can be considered unacceptable, and is indeed an indicator of future problems.

#### 2.4 Indicator 4: Total emissions

The indicator is the total amount of emissions within the region. In Section 2.2, several indicators have been defined regarding the *relative* amount of leakages or cycle losses, which is relevant information from the point of view of formulating policy measures. However, it is the *absolute* amount that is indicative for the environmental problems created by a certain chain management. For this, the total amount of emissions may serve as an indicator.

##### *Significance of the indicator*

It depends on what exactly counts as an emission, what the significance of this indicator is. In a strict sense, any transgression of the economy/environment border is an emission. However, generally a narrower definition is adopted: the emissions are the emissions into the atmosphere and surface water as well as the diffusive emissions into soils. When we consider environmental quality, the latter definition may be preferred, since this excludes the landfill sites where generally large amounts are stored but relatively little disperses from the location. In section 3.2 this issue is discussed further.

##### *Method of calculation*

The emissions can be extracted directly from the overview of flows and stocks.

##### *Interpretation for environmental policy*

For the interpretation, emission targets may be used if available. It may be necessary to break down the total emissions into categories, emissions to the various environmental compartments. Often, emission targets do not exist. In that case, "less is better" could still be used to compare alternatives. To follow the fate of the emissions through the environment and calculate the environmental concentrations resulting from the emissions is also possible, however, this would duplicate indicator 1 and would therefore be superfluous. It could be argued that using emission targets is merely a less sophisticated way to approach the environmental problems involved. On the other hand do emission targets often include policy objectives apart from environmental concern, for example political considerations.

If the analysis has included more than one substance, it may prove useful to make use of so-called equivalency factors, determining the contribution of individual substances to specific environmental problems (such as: acidification, global warming, smog formation etc. etc.). In that manner, substances can be compared according to their potential problem causing.

#### 2.5 Indicator 5: Depletion rate

##### *The significance of the indicator*

The indicator is the *contribution of the region to the global resource depletion*. It provides information with respect to the depletion of global resources as a result of the substance management within the region. The requirement of virgin material is determined by the region's consumption, i.e. the use flow (see indicator 5) and by the amount of recycling (see indicator 6). On that side, the information is already available from the other indicators. However, this information must be combined with information on the global extraction of the resource to put it in perspective. Even more perspective can be obtained by calculating this indicator on a per capita basis and then compare with the global average.

### *Method of calculation*

The general formula for this indicator is

$$F_{v,r} = F_{use} * (1 - I_R) / F_{v,g}$$

with  $F_{v,r}$  = global depletion rate of virgin material by region (%)

$F_{use}$  = use flow (kg/y)

$I_R$  = recycling rate (%), see indicator 6

$F_{v,g}$  = global extraction of virgin material (kg/y)

The per capita variant can be calculated by dividing the depletion rate by the number of inhabitants of the region, and compared with the global extraction divided by the world's population.

### *Interpretation for environmental policy*

For this indicator, it is very difficult to define a reference value, once again the "less is better" criterium can be used. For the per capita variant, the global average may be used as a reference value.

### 3 Indicators concerning the economic subsystem

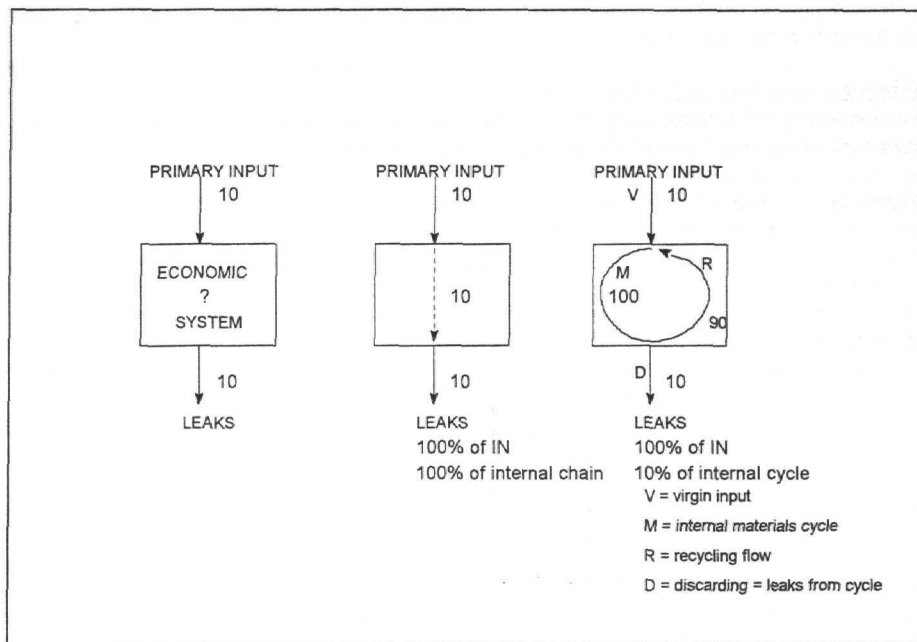
Indicators for flows and stocks in the economic subsystem bear no direct relation to environmental problems linked with the substances. This does not mean that such indicators are meaningless. In the first place, they provide information regarding the "tidiness" of the societal chain management: regardless of environmental problems, it still seems a good idea to keep the house in order by improving efficiency. In the second place, these indicators offer information directly relevant for actual policy measures. For example, it may become apparent whether a certain required emission reduction can be obtained by technical emission reduction, or that a source-oriented policy is required. In the second place, here too the concept of risk may be introduced: certain societal ways of using a substance may serve as an early warning of future environmental problems. Five indicators for chain management and early warning are proposed:

6. efficiency, i.e. the efficiency of the economic processes within the region
7. use level, i.e. the amount of the substance being used by the region's population
8. recycling rate, i.e. the fraction of waste being recycled within the region
9. economic accumulation, i.e. the increase in economic stocks during the year within the region
10. economic dissipation, i.e. the fraction of the substance's applications being trace applications.

#### 3.1 The economic substance chain and its nodes and flows

Figure 2 shows an extremely simplified version of the economic substance chain. The leftmost picture only shows that the system's inflow matches the outflow:  $OUT/IN = 1$ . However, this hardly provides information on the economic regime itself: are the processes within the economy efficiently conducted, is the substance recycled to any extent, can the economic cycle still be improved and if yes, how? The middle and rightmost picture show two extremes: in the middle picture, there is no economic cycle but a chain, all inflow directly "falls through" the economic system into the waste bin; the rightmost picture represents a cycle which is closed for 90% and wherein a much higher use value is acquired with the same input and output levels. To define meaningful indicators for the economic subsystem, therefore, we cannot limit ourselves to the borders of the system but must be more specific. This will be attempted below, where the five indicators for chain management are described in more detail.

Figure 2 The economic cycle and its losses



For a number of indicators, as will become clear in the following sections, it serves a purpose to split the economic system into smaller parts. We can distinguish here between categories of *nodes* or economic processes, and categories of substance *flows*.

Several indicators regarding the economic substance flows are defined using a "horizontal" splitting of the economic system into four subsystems representing life cycle stages: (1) extraction and refinery, (2) production and manufacturing, (3) use and consumption, and (4) waste treatment. With the wisdom of Figure 2 as a point of reference, a first rule is to define the subsystems in such a way that none comprises a recycling flow within itself. Secondly, while dividing the economic system into subsystems, no flow must be omitted or double-counted. Thirdly, there is a number of debatable issues in determining which node belongs to which subsystem. The position of trade for example is not clear, but has consequences for the destination of imports and the origin of exports. Another example is the use of products by industries, which are not directly connected to the production (cleaning agents, coffee cups, paper etc.). Also, the place of recycling processes, where metals are extracted from scrap, is not clear: does this belong to waste treatment, or is it part of refinery? The positioning of the nodes is rather critical for some of the indicators, therefore careful attention is required. For this report, the following choices have been made:

- trade has no special place, it can occur within any of the subsystems
- use of products not directly connected with production belongs to "use and consumption"
- scrap refinery is part of "extraction and refinery"
- agriculture as a whole is part of "production and manufacturing"; therefore this also includes the use of fertilizer and fodder as production factors.

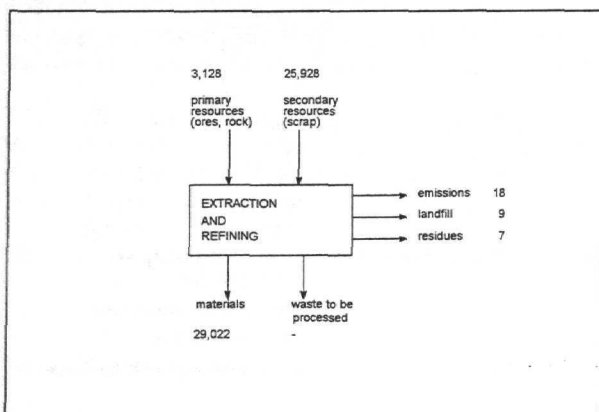
It is also possible to consider splitting the economic system vertically — for example, the food production and consumption column, or one specific source and its destinations. It then becomes possible to see the differences between the more or less separate cycles of applications that exist within

the economic system: cadmium from zinc ore vs. cadmium from phosphate rock, applications of metallic copper vs. applications of copper compounds, copper in the agricultural system vs. copper in the transport system, and so on.

### Subsystem Extraction and Refining

The Extraction and Refining subsystem contains processes with regard to mining and refining. Also, the secondary recovery of substances from scrap or compound waste forms a part of this system.

**Figure 3a** Subsystem Extraction and Refining

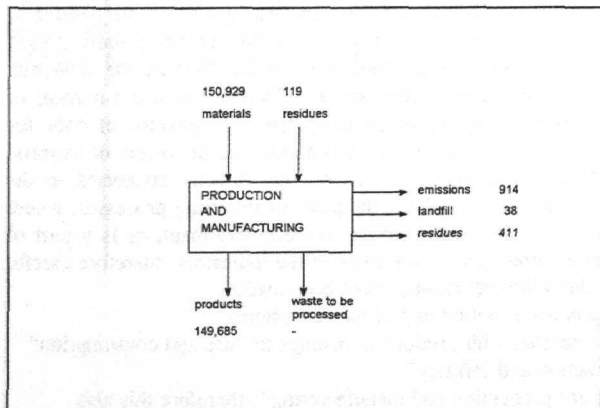


This means a leakage percentage of 0,1%. Of course, no real extraction of copper takes place in the Netherlands. The figures here have bearing on secondary recovery of copper from scrap, and on the refining of iron, zinc and phosphate rock. The losses from this subsystem constitute 0.2% of the total losses from the economic system, being 15,658 tonnes of copper (see also Table 1).

### Subsystem Production and Manufacturing

The Production and Manufacturing subsystem comprises all activities and sectors that use minerals or other material resources (in this case, copper) to manufacture useful products. Which of these are relevant is something that must always be decided upon for the individual substance in question.

**Figure 3b** Subsystem Production and Manufacturing



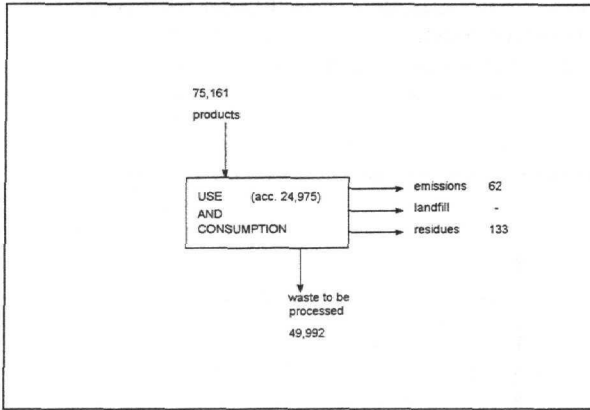
In this subsystem, the leakage percentage is 1%. Nevertheless, 8.7% of the total losses from the economic system takes place in this subsystem: it is a relatively large subsystem in the sense that large flows of copper are involved.

### Subsystem Use and Consumption

In the Use and Consumption subsystem, the commercial users and the households or consumers constitute a key group. The subsystem also includes applications in the construction industry, in transport systems and even in industry (production subsystems). Waste that is still to be processed is

not considered a leakage, because in the Waste Processing subsystem it may be used to produce secondary resources.

Figure 3c Subsystem Use and Consumption

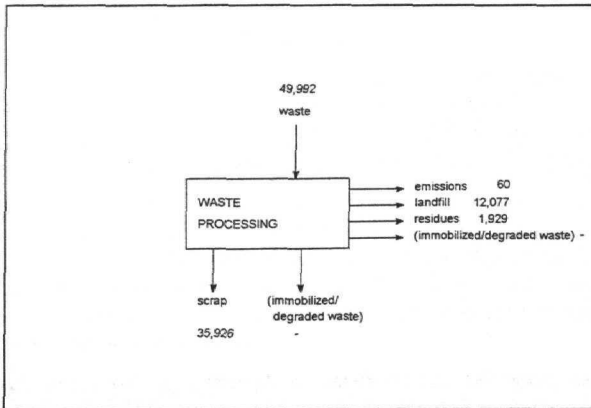


The leakage in this subsystem is 0,2%, again small. It constitutes 1.2% of the total losses from the economic system. However, the outflow here is only 66,5% of the inflow. The remaining amount accumulates. This means that the leakage for the steady state situation maybe higher, although probably still very low (<1%).

Waste processing subsystem

This subsystem, defined for copper in the Netherlands in 1990, comprises scrap recycling, waste incineration, sewage treatment, composting and landfill. Not only municipal, but also industrial waste treatment is part of this subsystem. The input consists of the scrap and waste to be processed, the output of secondary resources and, possibly, completely immobilized or degraded waste. Compost and sewage sludge constitute a separate category: to a certain extent these are reused in the agricultural sector as a fertilizer. However, one can ask whether this ought to be classified as a functional output. For metals, at any rate, it can be argued that this is in fact a leakage from the cycle: recycling in agricultural produce is undesirable, and any further functional use of the metals is out of the question.

Figure 3d Subsystem Waste Processing

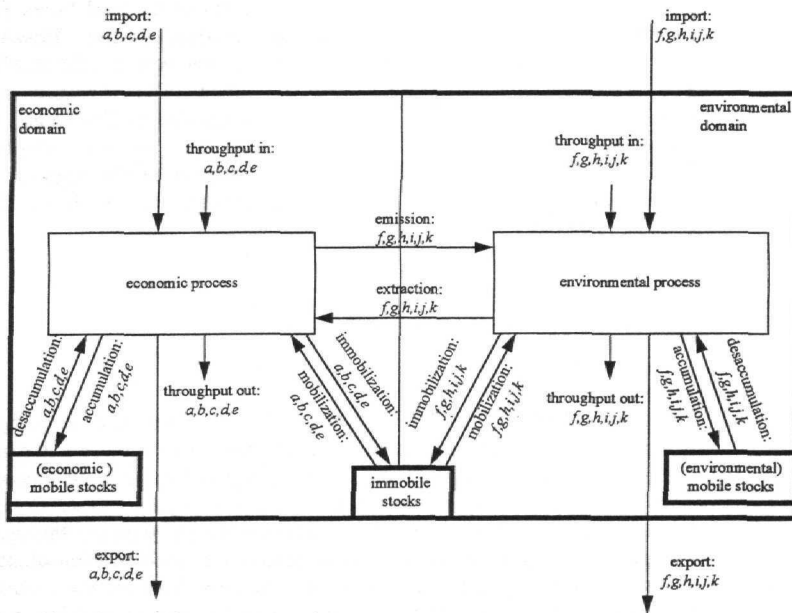


This subsystem has a leakage percentage of 28, much higher than in the other life-cycle stages. The contribution to the total losses from the economic system is large: 89.8%. Both in a relative and in an absolute sense, the losses from the Dutch copper chain obviously occur mainly in the waste stage. It should be noted that on a global level this need not be true: large losses are connected with the mining of copper, which do not show in the Netherlands due to the absence of copper mines.

A next issue is the classification of the various *flows and stocks*. This also is important for several of the indicators discussed in the next sections. Figure 4 represents a general classification.

**Figure 4: Categories of flows and stocks**

(in the figure only one economic process and one environmental process are drawn as example, but a system of course generally includes many more processes).



**Legends:**

Substance in:

- a) final waste
- b) non-functionally in recycled products, materials, wastes etc.
- c) functionally recycled as substance or in products, materials, wastes etc.
- d) non-functionally in products, materials, wastes to be processed etc.
- e) functionally as substance or in products, materials, wastes to be processed etc.
- f) air
- g) water
- h) soil
- i) sediment
- j) groundwater
- k) sea

A more detailed description of these categories can be found in Appendix 1. To apply this classification in practice still requires a number of choices. For example, it may be useful to make a distinction between emissions and chain losses or leakages, because not every flow within the economic system can be considered economically useful. For the definition of "leakage", a choice can be made from a number of feasible criteria:

- every output whereby the substance does not intentionally end up in a product or resource is a leakage (emissions, degradation, immobilization, waste, sewage plant outflows, manure, compost, incineration residues and scrap)
- every output from which the substance cannot be recovered or reused is a leakage (emissions, degradation, immobilization, incineration residues and waste)
- every output that does not subsequently serve as an input to a new economic process is a leakage (emissions, degradation, immobilization and landfilling of final waste)
- every output that directly enters the environment is a leakage (emissions and landfilling of final waste).

The choice may vary with the aim of the study concerned. In the case of the metals programme, as a provisional choice, the following have been taken as leakages:

- emissions
- landfilling of final waste
- incineration residues in which the metals are present as contaminants, independent of subsequent use of these residues.

Immobilization and degradation in fact constitute a loss from the economic cycle and may be regarded as a leakages from a resource conservation point of view, because the lost materials will have to be replaced by fresh input. If resource conservation is no issue, as is the case for example with chlorine or nitrogen compounds, then immobilization or degradation of waste into a harmless form can be equally desirable, or even more so, than recycling. The decision to include these outflows thus would depend on whether the substance in question is related to a depletion problem as well as to pollution. For the Dutch situation regarding copper in 1990, the immobilization route was not present and therefore not included.

### 3.2 Indicator 6: Efficiency

The indicator is the *efficiency of the economic processes within the region*. Process efficiency is mostly calculated as OUT/IN, whereby the losses to the environment are extracted from OUT. Figure 2 shows that calculating OUT/IN makes no sense for the system as a whole. On the other hand, we want an indicator on a more aggregated level than that of single processes. Therefore, a choice is made to use the life cycle stages as defined in Section 3.1 and establish efficiency for those subsystems. The efficiency in fact is the reverse of the leakages: it is the *fraction of the inflow that ends up in another economic process*.

#### *The significance of the indicator*

The efficiency of a comprehensive group of processes indicates the appropriateness of the processes and techniques involved. The factors determining the "appropriateness" vary with the life cycle stage. For the "extraction" and "production" subsystem, it indicates the possibilities for closing the cycle by technical means: the adoption of more efficient production techniques, or a better application of the current ones. For the "use" subsystem, the efficiency is related to two aspects: the life span of the applications, and the percentage of the household waste that is collected to be treated further in one way or another. The "waste management" subsystem's efficiency is determined by the amount of the substance recovered as secondary materials, and by the amount degraded or immobilized.

#### *Method of calculation*

For each subsystem an efficiency percentage can be calculated, in terms of the flow classification out of Figure 4, according to:

$$E_{lcp} (\%) = \frac{\sum_{i=a}^e F_{\text{export}, i} + \sum_{i=a}^e F_{\text{thr out}, i} - \sum_{i=f}^k F_{\text{emission}, i} - F_{\text{thr out}, a} - F_{\text{immobilization}, a} - F_{\text{export}, a} - F_{\text{accumulation}, a}}{\sum_{i=a}^e F_{\text{import}, i} + \sum_{i=a}^e F_{\text{thr in}, i} + \sum_{i=a}^e F_{\text{mobilization}, i} + \sum_{i=a}^e F_{\text{desaccumulation}, i} + \sum_{i=f}^k F_{\text{extraction}, i}} * 100\%$$

where  $E_{lcp}$  is the efficiency of a life cycle phase,  $F$  indicates a flow, thr out is the throughput out and thr in is the throughput in.

An issue that must be dealt with for the indicator is the issue of time delay, in the shape of the economic accumulation. This accumulation is neither a "useful" outflow nor yet a loss from the economic cycle. To elude this problem, calculating the long-term steady state may prove to be the best basis for the comparison of different regimes: it is the situation in which the ultimate fate of the accumulation is determined and all of the inflow can be attributed to either a useful outflow or a leakage. Another option is, not to determine the fate of the inflow but to look only at the outflow: it then can be determined which fraction of the total outflow out of each subsystem enters another subsystem and which fraction can be classified as leakages.

#### *Interpretation for environmental policy*

As a general rule, it can be stated that - quite apart from economic considerations - the higher the efficiency of the processes is, the better it is. An efficiency of 100% therefore, although this can never be realized, may serve as a target. But there is more information to be extracted from this efficiency indicator. In the first place, the life-cycle stage which is responsible for the biggest losses can be identified. In various case studies, it has been shown that the largest leakages no longer occur in the production stage, but in the use or waste management stage, depending on the substance and the application. Secondly, the efficiency per life-cycle stage provides a measure to compare different techniques or options for production, user behaviour and waste management. Thirdly, the efficiencies of different sectors within the economy can be compared. Finally, different substances can be compared, which may provide some policy relevant information as well. In Table 1, the efficiency percentages for six heavy metals in the Netherlands are presented.

A remarkable difference can be seen between the more bulky metals Cu, Zn, Pb and Cr on the one hand, and the small-scale metals Cd and Hg on the other hand. The losses from all life-cycle stages are much larger for Cd and Hg. Partly, this is due to the low recycling rate. It also may have to do with the relatively large non-intentional flows for Cd and Hg, which will be treated in more detail in Section 3.6. For lead, the recycling percentage is highest. For zinc, the high efficiency in the waste stage is due partly to a large export of waste, mainly scrap, to be treated elsewhere. It may be considered to follow the fate of exported waste and demand a correction to the waste treatment efficiency accordingly. On the other hand, this is not relevant for the region's own waste management regime, which is the only waste management to be influenced by a region's policy. Theoretically, a region's policy could be directed (intentionally or not) at exporting this life-cycle stage and thus the pollution would be exported. This is discussed further in Section 4.1: problem shifting to other regions.

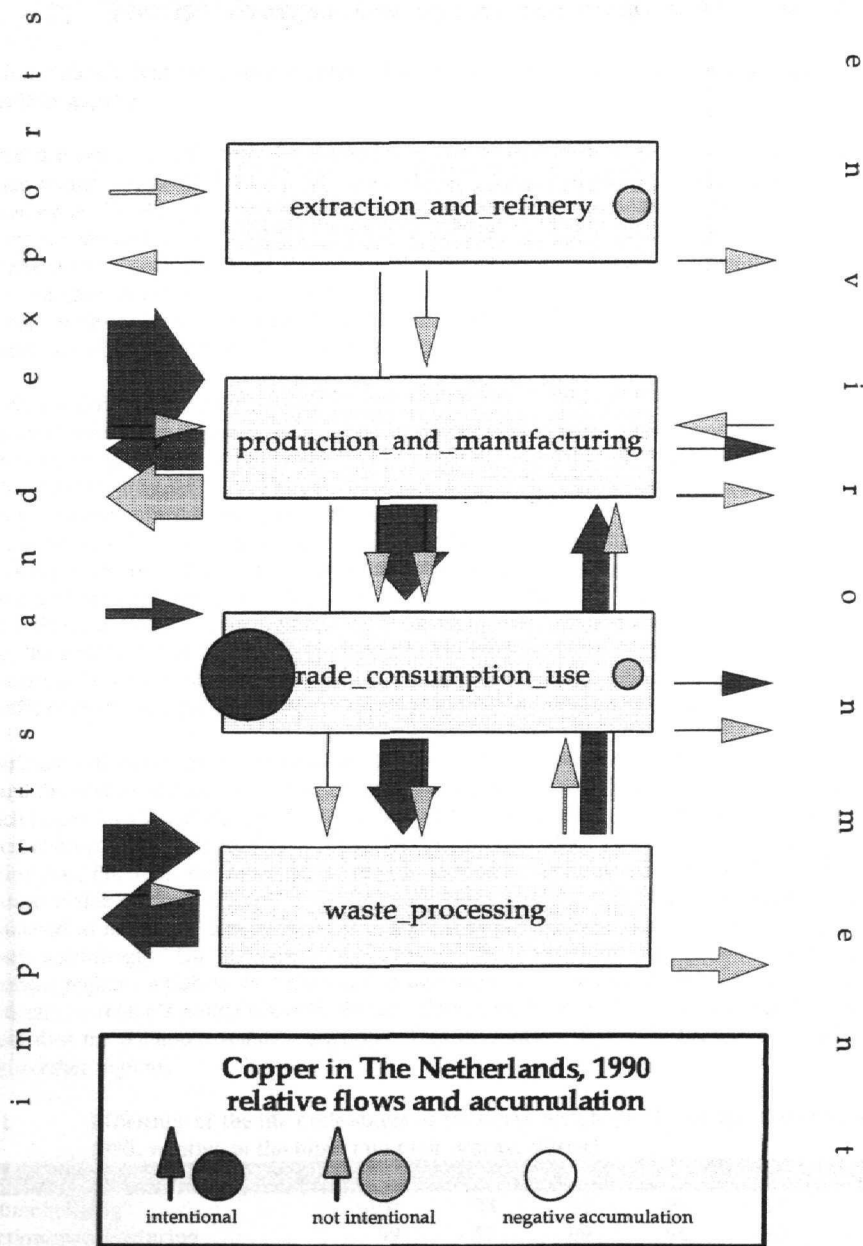
**Table 1** Efficiency of the life cycle stages of six heavy metals (in %, for the Netherlands, 1990, relative to the input into each process cluster)

	Cu	Zn	Pb	Cr	Cd	Hg
extraction/refining <sup>1</sup>	100	98	92	94	87	39
production/manufacturing	99	97	99	96	80	59
use/consumption	100	94	98	100	86	85
waste treatment	72	84	94	89	57	27

<sup>1</sup> Only recovery from scrap and refining of iron, zinc and phosphate ores (no mines in the Netherlands)

In Figure 5, a summary is presented of the copper chain in the Netherlands in 1990, divided into its four subsystems, in which the imports, exports and accumulations have been made visible. For each life cycle stage, the efficiency is indicated. It appears that the largest inefficiencies can be found in the waste treatment subsystem. For more details, see Van der Voet (1996).

**Figure 5 The economic copper cycle for the Netherlands, 1990**



### 3.3 Indicator 7: Level of use

The indicator is the amount of the substance being used within the region. The indicator refers to M in Figure 2: the magnitude of the economic cycle.

#### *The significance of the indicator*

The total amount of use within a region determines, directly or indirectly, all other economic flows. It is therefore a measure of the total economic throughput.

#### *Method of calculation*

For the use level, a choice must be made for either the total use *flow*, which is the flow of newly produced goods into the use/consumption stage, or the total use *stock*. Both can be derived from the overview of flows and stocks directly. It depends on the substance, or rather on the application, which one makes the most sense. For metals, the use stock seems the appropriate choice, since most applications have a life span of more than one year: the inflow required to keep up the stock is small in comparison to the stock, while the stock's size determines the generation of waste. When stock data are missing or very incomplete, the use flow may be appointed as a proxy. For a substance such as nitrogen, the use flow is indicated, since the N-flows are for the most part agricultural flows with a high turnover rate. The use flow as well as the stock can be extracted directly from the overview. The total use flow or stock can be obtained by adding all separate flows or stocks.

In the case of copper in The Netherlands, the use flow is 75,161 tonnes/year in 1990. The use stock is not known; for copper applications in the residence building sector alone it is estimated at 340,000 tonnes (Fraanje & Verkuijlen, 1996).

#### *Interpretation for environmental policy*

No reference value can be defined regarding the level of use. For this indicator, again the "less is better" adagium can be adopted, since in accordance with ideas of dematerialization less use generally means less input, and therefore less emissions. For certain substances, a volume policy can be imagined, which goes hand in hand with the definition of a volume reduction target. Such a target could be applied to the use level, either stock or flow. It may be stated here once again, that this indicator (as all the others as well) should be used only in combination with others in order to derive meaningful information from it.

### 3.4 Indicator 8: Recycling rate

The recycling rate within the region refers to the relative amount of generated waste which is, in one way or another, transferred into a useful input for an economic process. Its counterpart is the discarding rate, the relative amount of waste being emitted into the environment. In a steady state situation, the discarding rate equals the required virgin input rate according to  $IN = OUT$ , as can be concluded from Figure 2.

#### *The significance of the indicator*

The recycling rate - or its counterpart the discarding rate - of waste materials, can be an indication of the "closedness" of the economic substance cycle. It indicates the leakage percentage of the economic cycle as a whole, and, vice versa, the potential for a further "closing of cycles" policy. In other words, if a cycle that is closed for 99.99% still leads to harmful losses to the environment, there is not much more to be expected from measures in the field of technical emissions abatement and recycling. In such a case, a volume policy of some sort is indicated. If, on the other hand, the virgin input is large compared to the amount of recycled materials used, the efforts toward a technical closing of the leakages may be effective.

### Method of calculation

The general formula for the recycling rate in % per life cycle phase is, according to Figure 4:

$$R_{\text{lep}} = \frac{F_{\text{export, c}} + F_{\text{thr out, c}} + F_{\text{immobilization, c}}}{\sum_{i=a}^e F_{\text{export, i}} + \sum_{i=a}^e F_{\text{thr out, i}} + \sum_{i=a}^e F_{\text{immobilization, i}} + \sum_{i=f}^k F_{\text{emissions, i}}} * 100\%$$

A decision has to be made regarding which flows to include as recycling flows: is it only the intentional re-use and recovery of metals, or also the use of metals in secondary materials such as fly-ash, compost or manure. In the formula above, the first approach is taken.

The main difficulty in calculating the recycling rate is the economic accumulation, or in other words the time delay between inflow and discarding. Of the accumulated materials, it is unknown whether they will end as an emission or as a secondary material. The calculation of the steady state situation belonging to the substance's economic regime can be used once again to solve this problem. In the steady state, no accumulation exists and the fate of the total inflow is known. A less elaborate procedure is to extrapolate the relative recycling percentages for the various applications to the total of the inflows into the use system. In the absence of detailed information with regard to the system's stocks this approach will be quite adequate.

For the flows of copper in the Netherlands, an example of the second calculating procedure (since no stock data are available) is shown, containing only the intentional Cu applications. Thus, copper as an additive in fodder is included, copper in manure is not. The amount of materials to be recycled varies with the application. Therefore, the percentage was calculated for different applications, as is shown in the Table 2 below. The figures refer to the steady state situation belonging to the 1990 copper regime of The Netherlands.

**Table 2** Recycling of discarded copper products, The Netherlands' 1990 regime, steady state situation.

application	Cu use flow (tonnes/y, 1990)	recycling rate (%)	recycling flow (tonnes/y)
consumer products	60,019	59	35,264
construction	10,342	98	10,135
water pipes	1,120	89	997
tram/train wires	540	94	508
navigation	160	0	0
food	726	0	0
<b>TOTAL</b>	<b>72,907</b>	<b>64</b>	<b>46,904</b>

The "leakage" therefore is  $100\% - 64\% = 36\%$ , or 26,003 tonnes.

### Interpretation for environmental policy

The recycling rate may serve as a measure of the efficiency of the economic system as a whole. As a target level, a 100% recycling can be said to completely prevent both depletion and pollution problems. In practice, this will never be attained. A region-specific and substance-specific "acceptable" or "sustainable" leakage may be defined with the help of environmental quality standards. This, however, is an absolute leakage, not a relative one, and moreover this may better be addressed by indicators regarding the economy-environment interface as treated in Section 2.3.

As a relative indicator for the economic cycle, the lower leakage percentage may be interpreted as the better one.

### 3.5 Indicator 9: Economic accumulation

The indicator is the *increase in the economic stocks in the region over the year*. Accumulation of substances in the economy takes place in materials and products. On a minor scale, stock building can be detected in industrial stocks of raw materials and products for sale. By far the largest economic stocks can be found in the use or consumption phase of the substance's life-cycle: in products used in households, in materials locked up in buildings, roads, equipment, vehicles, etc. Accumulation of waste takes place on landfill sites. However, accumulations of this latter type can be regarded as losses from the economic chain, and therefore as environmental accumulations. Specific stocks may be chosen, but the indicator can also be defined on an aggregate level.

#### *The significance of the indicator*

In itself, accumulation in materials and products does not constitute a problem: there is no leakage to the environment. What accumulation does mean, though, is a lack of equilibrium in the economic system. Growing stocks indicate a risk of leakages and/or waste volumes growing in magnitude in the future. Since it is difficult to appoint "key" stocks in the economy, the economic accumulation indicator may best be composed out of the total of all accumulations. Different applications may have varying life expectancies. Cadmium, for example, occurs in plastics as a pigment or stabilizer, but also in building materials through application of Cd-containing fly ash. Whereas packaging materials will complete their life cycle within the year, buildings may "live" for centuries and cadmium in bricks or cement might cause risks for generations in the distant future. Eventually, the regime will tend toward a steady state situation with larger stocks and therefore larger "leakages" which can be calculated. Accumulation in the economy thus functions as a warning signal of future environmental problems.

#### *Method of calculation*

This indicator can be extracted directly from the overview of flows and stocks.

#### *Interpretation for environmental policy*

In contrast to environmental accumulation, economic accumulation cannot be translated directly into policy relevant terms with the help of environmental quality standards. No such standards exist, nor can they be imagined, for economic stocks. In this case, no target level can be introduced. As a general rule, it can be stated that in otherwise comparable systems a higher accumulation means a less stable (i.e. more different from the steady state) situation, and therefore a larger risk for increased emissions in the future. The indicative value is thus relative, not absolute. Some rather diffuse and vague feeling for "how bad it is" may be obtained by comparing the accumulation with other flows or stocks in the system, for example, the system's total inflow, the size of the use flow (total inflow into the "use" nodes), or the size of the total economic stock. Probably, the comparison with the use stock or - if the stock size is unknown - the use flow will provide the best reference, since import and export do not influence this figure. For copper in The Netherlands, the accumulation in user stocks amounted to roughly 25,000 tonnes in 1990. This is about a third of the use flow, which was 75,000 tonnes, and it caused the stock to grow by approximately 2.5%.

For a further interpretation, it is advisable to establish what kind of an equilibrium a given regime is tending towards in the absence of additional measures. By calculating the steady state situation belonging to the regime, the economic accumulation is translated into the **generation of future waste and emissions**, which can be evaluated as described in Section 4.3 in order to determine

their acceptability. Different applications of a substance have different life spans. This life span can be used not only to determine the steady state discarding rate, but also for specifying the time period involved in reaching the steady state situation. The application with the longest life expectancy obviously determines the length of time until equilibrium is reached. Another way to estimate the time of impact is to calculate some sort of "average levelling off period", wherein the bulk of the application, as well as the life span, plays a role .

Another option is, to make a distinction according to the life span involved in the delay. Accumulation of short-lived products can be regarded as only obscuring the "real" picture regarding the generation of waste and emissions. Long delays on the one hand involve much more uncertainties regarding the amount of waste and emissions being postponed and the time of their final release. On the other hand, a very long-term delay may actually prevent emissions and could in some cases be regarded as beneficial. To distinguish short- and long term accumulation therefore seems to make sense.

### 3.6 Indicator 10: Economic dissipation

The indicator is the *fraction of the applications in the user phase that can be called trace applications*. Dissipative applications are becoming increasingly important as pollution sources. Perhaps the most dissipative applications of metals is the application as a trace element in products. A large part of these applications in fact are non-intentional: the occurrence as product pollutants in, for example, phosphate fertilizer or fossil fuels. Product policies, such as for example the Cadmium Directive (Council of the European Communities, 1991), are directed against such trace applications, the intentional as well as the non-intentional ones. As a result of waste management policies however, the trace applications increase: waste materials such as manure, fly ash, compost and sewage sludge, wherein metals tend to accumulate, are increasingly re-used. Thus, discarded metals start a second economic life-cycle as a contaminant of such secondary materials. To honor the importance of this phenomenon, the relative amount of trace applications is proposed as an indicator.

#### *The significance of the indicator*

The indicator is a measure of the preventability of emissions from the economic chain or cycle.

#### *Method of calculation*

This indicator requires information that does not show out of the overview of flows and stocks, but is used in the process of quantifying the overview: the breaking down of either the use flow or the use stock into the separate products, and the composition of those products. Based on that information, a classification can be made into trace and bulk applications. If applied to flows, the formula then is as follows:

$$T_u (\%) = \frac{\sum_{ti=ta}^{ik} F_{import, ti, u} + \sum_{ti=ta}^{ik} F_{thr in, ti, u} + \sum_{ti=ta}^{ik} F_{mobilization, ti, u} + \sum_{ti=ta}^{ik} F_{desaccumulation, ti, u}}{\sum_{i=a}^k F_{import, i, u} + \sum_{i=a}^k F_{thr in, i, u} + \sum_{i=a}^k F_{mobilization, i, u} + \sum_{i=a}^k F_{desaccumulation, i, u}} * 100\%$$

with  $ti$  indicating the trace applications within category  $i$  and  $u$  indicating the use phase.

**Table 3** The magnitude of the bulk and the trace economic cycles for copper in the Netherlands, 1990 (inflow into subsystems, tonnes Cu/year).

	bulk	trace	%trace
extraction/refinery <sup>1,2</sup>	26,000	3,130	11%
production/manufacturing	151,000	522	0.3%
use/consumption	75,000	5,400	7%
waste treatment	50,000	283	0.6%
accumulation	22,000	5,370	20%
emissions <sup>3</sup>	139	1,220	90%
total chain losses <sup>4</sup>	11,979	3,746	24%

<sup>1</sup> Only recovery from scrap and refining of iron, zinc and phosphate ores (no copper mines in the Netherlands)

<sup>2</sup> The figures refer to the inflow into the subsystem. Due to imports and exports, the subsystems do not connect.

<sup>3</sup> Emissions to the atmosphere, surface water and diffusive soil emissions

<sup>4</sup> Emissions and landfill.

#### *Interpretation for environmental policy*

Since trace applications are much more difficult to recycle, and emissions from trace applications are much more difficult to prevent compared with bulk applications, it could be concluded that the lower the share of trace applications is the better it is for the prevention of chain leakages. From Table 3 it shows plainly that, although for copper the trace cycle is small compared to the bulk cycle, the main emissions originate from the trace cycle.

#### 4 Indicators concerning the relation of the economic subsystem to the environment and to other systems

In the end, the measure of the sustainability of a certain substance regime lies in the economy-environment interaction: the leakages from the economy to the environment on the one hand, and the extraction of natural resources from the environment for economic purposes on the other. The relative size of the leakages determine the possibilities to reduce these further by technical measures. The absolute size on the other hand determines the absence or presence of pollution problems and therefore environmental quality. In the same manner is the relative virgin input a measure for how much this input still can be reduced without loss of functions, while the absolute amount determines the size and speed of depletion problems.

Another way of linking the two concepts sustainability and environmental quality is to compare the economic and the environmental substance chain or cycle. Such a comparison may serve as a measure for *risk*. In the first place, an economic cycle that is large compared to the natural one indicates a high risk of disrupting the natural cycle by its losses, even if the economic cycle is relatively "closed". In the second place, the risk of the process of de-linking itself is indicated: a relatively large economic cycle indicates relatively big difficulties in case we have to fall back to the natural system for providing the desired functions. This type of comparison is especially relevant for substances such as nitrogen (N) or carbon (C), for which large biogeochemical cycles exist. To see that humans have by their activities doubled the natural N-cycle creates a powerful image. For trace elements such as metals the comparison is less eloquent. The human cycle often is very large compared to the small natural one.

Two indicators are proposed within this category:

11. pollution footprint, i.e. the total amount of emissions anywhere on the world, on behalf of consumption and use within the region
12. disturbance rate, i.e. the magnitude of the economic cycle compared to the natural cycle.

##### 4.1 Indicator 11. Pollution footprint and pollution export

The pollution footprint is the *total amount of emissions on behalf of consumption within the region, occurring anywhere on the world*. Several studies show the process of the "cleaning up" of regions during the last decades (Ayres & Rod, 1986; Stigliani & Anderberg, 1992). Such a process is accompanied by a shifting of emissions from industrial point sources to diffusive consumer emissions. One of the possible side effects of the cleaning up of a region is the shifting of environmental problems to other areas. Especially in regions with rather strict environmental regulations, the more polluting stages of the life cycle may be relocated outside the area. On the global level this may even lead to more pollution. Therefore, insight into the pollution occurring - anywhere in the world - on behalf of the consumption of the region's population is useful. Here, an indicator is defined to measure this problem-shifting away from the region in relation to developments within the region.

##### *The significance of the indicator*

The pollution footprint, when compared to Indicator 9, is a measure of the occurrence of the benefits and the problems of the use of a substance within the same area, or, in other words, the (implicit) problem-shifting practices of a region.

### *Method of calculation*

In specifying a region's substance life cycle there are two possible points of departure, each resulting in a different idea of what does and what does not belong to the cycle. The two approaches can be characterized as "regional" and "functional". *It is precisely the difference between those definitions that is a relevant measure for the pollution export indicator.*

The point of departure for the regional approach is the area as a geographically bounded system. The location determines which steps in the life cycle (extraction/production/consumption/waste processing) take place within the system, and to what extent. In establishing the amount of pollution, all of these are then included, even if production is for consumption elsewhere. As a result, a picture emerges of the pollution occurring within the region, identical to indicator 9 (total emissions).

For the functional approach, the point of departure is the fulfilment of functions for the population of a given region. The first step is to establish the consumption of the substance within the region; this serves as the basis for establishing the full extent of the cycle. Any relevant steps taking place outside the region must then also be included, as must any leakages. In the inventory stage this may imply additional problems. Those steps in the cycle taking place within the region for the benefit of other countries are excluded. As a result, no picture is obtained of the regional environmental situation. Taking cadmium as an example, what is obtained is something that might be described as the "Life Cycle Assessment of cadmium consumption": a picture of the cadmium leakages occurring throughout the cycle for the benefit of the regional population, regardless of the location of those leakages - which is also useful information. This approach has a certain resemblance to what Rees & Wackernagel (1992) call the *ecological footprint*. They refer to the fact that an urban area requires much more space than its actual territory in order to provide for its inhabitants. In the case of the *pollution footprint*, "space" must be taken metaphorically. Instead of "The Netherlands actually occupy three times their territory", the conclusion could be something along the lines of "The Netherlands are in fact responsible for three times the pollution that they actually have within their borders".

In practice, this approach is extremely demanding of time and data, not only with regard to the region itself but also with regard to processes in other regions. Therefore, a simplification is proposed in which the regional situation is examined first, and in addition consideration is given both to the extent to which parts of other region's cycles (i.e., extraction, production and waste treatment processes connected with consumption in other regions) are carried out within the region, and the extent to which the region farms out parts of its cycle to other regions. This, in fact, boils down to a *calculating of the "self-sufficiency"* of the region with regard to the various life-cycle stages of a substance. The central life-cycle stage again is the "use" stage, because it indicates the region's needs. This can be translated "upchain" into a required production and recovery level and "downchain" into a required amount of waste treatment. The required levels of extraction, production and waste treatment can be compared with the actual level as it presents itself in the overview of flows and stocks, and thus self-sufficiency can be calculated for each life-cycle stage.

To move one step further in the direction of the "real" pollution footprint, a theoretical leakage for each life-cycle stage can be calculated by dividing the actual leakage by the self-sufficiency fraction, to obtain a "reference leakage" which approaches the actual functional leakage. The implication is then that the regional leakage is representative of the total of processes required for the supply of the region. In the example below, this could lead to inaccuracies especially for the extraction/refining subsystem, because no mining takes place in the Netherlands and the concurrent losses are unknown.

In the end, to obtain the pollution export indicator, the regional leakages are extracted from the footprint leakages. The remaining amount is the pollution export: not that this can also be a negative figure, in which case one could speak of pollution *import*.

A more formal representation is the following:

The pollution footprint is calculated in three steps:

(1) calculation of the self-sufficiency (SS) per life-cycle phase:  
for the use phase (u):

$$SS_u = 1$$

for the production phase (p):

$$SS_p = \frac{\sum_{i=a}^k F_{\text{export}, i, p} + \sum_{i=a}^k F_{\text{thr out}, i, p} + \sum_{i=a}^k F_{\text{immobilization}, i, p} + \sum_{i=a}^k F_{\text{accumulation}, i, p}}{\sum_{i=a}^k F_{\text{import}, i, u} + \sum_{i=a}^k F_{\text{thr in}, i, u} + \sum_{i=a}^k F_{\text{mobilization}, i, u} + \sum_{i=a}^k F_{\text{desaccumulation}, i, u}}$$

for the extraction phase (e):

$$SS_e = \frac{\sum_{i=a}^k F_{\text{export}, i, e} + \sum_{i=a}^k F_{\text{thr out}, i, e} + \sum_{i=a}^k F_{\text{immobilization}, i, e} + \sum_{i=a}^k F_{\text{accumulation}, i, e}}{\sum_{i=a}^k F_{\text{import}, i, p} + \sum_{i=a}^k F_{\text{thr in}, i, p} + \sum_{i=a}^k F_{\text{mobilization}, i, p} + \sum_{i=a}^k F_{\text{desaccumulation}, i, p}} * SS_p$$

for the waste management phase (w):

$$SS_w = \frac{\sum_{i=a}^k F_{\text{import}, i, w} + \sum_{i=a}^k F_{\text{thr in}, i, w} + \sum_{i=a}^k F_{\text{mobilization}, i, w} + \sum_{i=a}^k F_{\text{desaccumulation}, i, w}}{\sum_{i=a}^k F_{\text{export}, i, u} + \sum_{i=a}^k F_{\text{thr out}, i, u} + \sum_{i=a}^k F_{\text{immobilization}, i, u} + \sum_{i=a}^k F_{\text{accumulation}, i, u}}$$

(2) calculation of footprint emissions per life-cycle stage ( $F_{\text{life cycle phase}}$  in kg/y):

$$FP_{\text{lep}} = \frac{\sum_{i=f}^k F_{\text{emissions}, i, \text{lep}}}{SS_{\text{lep}}}$$

(3) calculation of the total footprint of the system studied (F):

$$FP = \sum_{\text{life cycle phase=extraction}}^{\text{waste management}} FP_{\text{life cycle phase}}$$

The pollution footprint can be compared to the region's total emissions (see indicator above) to get an impression of the region's pollution export. The pollution export (P) can be calculated as follows:

$$P = FP - T$$

Below, an example is presented for copper in the Netherlands, where the 1990 situation is compared with two possible situations in 2010: a package of measures conforming to current expectations, and another package of rather strict additional measures.

As we can see, The Netherlands' self-sufficiency is low for the extraction stage, but very high for the production stage. Overall, The Netherlands is a net importer of leakages and therefore has a negative score on the pollution export indicator. This is not expected to change by already agreed upon policy measures. From this table, it can be seen clearly that the pollution export indicator does not provide information with regard to the situation within the region: the absolute size of the leakages decreases considerably, while the pollution export indicator remains at the same level. As stated before, this indicator should only be used in concurrence with others.

**Table 4** Pollution footprint and pollution export for copper in the Netherlands

	1990 regime			2010 regime, accepted & intended policy		
	self suff. <sup>1</sup>	pollution region <sup>2</sup>	pollution footprint <sup>3</sup>	self suff. <sup>1</sup>	pollution region <sup>2</sup>	pollution footprint <sup>3</sup>
<b>extraction/refining</b>	38%	34	90	60%	31	52
<b>production/manufacturing</b>	199%	1,363	685	210%	873	416
<b>use/consumption</b>	100% <sup>4</sup>	195	195	100% <sup>4</sup>	208	208
<b>waste treatment</b>	100%	14,133	14,133	100%	8,672	8,672
<b>TOTAL leakages</b>		15,725	15,103		9,784	9,348
<b>pollution export<sup>5</sup></b>			-622			-436
			-4%			-4%

<sup>1</sup> self sufficiency per life-cycle stage, obtained by dividing the regional total input by the reference total input per life-cycle stage

<sup>2</sup> regional leakages, occurring within the borders of the region, in tonnes/year, obtained from the SFA overview of flows and stocks

<sup>3</sup> pollution footprint, i.e. pollution occurring anywhere on behalf of consumption by the regional population, in tonnes/year, calculated per life-cycle stage: regional leakages(tonnes/year)/(self-sufficiency \* 0.01)

<sup>4</sup> consumption, as the starting point, automatically has a self-sufficiency of 100%

<sup>5</sup> absolute: obtained by subtracting the TOTAL regional leakages from the TOTAL reference leakages; relative: obtained by dividing the net export of leakages by the TOTAL reference leakages

#### *Interpretation for environmental policy*

A reference value of a 0% pollution export, indicating that the region's pollution footprint matches the pollution occurring within the region, would seem a logical choice. However, the problem-exporting or problem-importing practices of a region cannot be judged absolutely. If, as in this example, the self-sufficiency for the "extraction" stage of the copper cycle in the Netherlands is low, this is not due to a problem-exporting policy but simply to the fact that there is no copper to be mined within the territory. If, on the other hand, the Dutch "waste management" self sufficiency were low, we could indeed speak of deliberate problem-exporting. Another possibility is the "less-is-better" approach: the smaller a region's footprint, the better it is. The pollution footprint can thus be used to compare one region with another, one (policy) regime with another, or different possibilities for development with one another.

Another issue is the size of the region. The smaller the region, the larger the incongruencies will be between the presence of the various life-cycle stages, the farther the self-sufficiency may be from 100% either up or down, and the less valuable the pollution export indicator will be. At least the national level seems to be indicated.

## 4.2 Indicator 12: Disturbance rate

The indicator is the *amount of emissions entering the environment compared to the natural generation of the substance within the region.*

### *The significance of the indicator*

The indicator is defined to provide information with regard to the risk that the natural substance cycle will be disturbed by human activity, in the shape of the economic substance cycle. Two ways of approaching this risk are presented below.

### *Method of calculation*

The extent to which the natural cycle is disturbed by human interference can, as a first possibility, be expressed by relating the natural "virgin" generation of the substance (by formation or erosion) to the anthropogenic adding (by emission):

$$r_d = \Sigma (F_{em}) / \Sigma (F_{genv})$$

with  $r_d$  = disturbance rate

$\Sigma (F_{em})$  = total emissions of the substance from the economic subsystem (kg/y)

$\Sigma (F_{genv})$  = total "natural" generation of the substance within the environmental subsystem (kg/y), either by formation or by erosion.

A second way to provide an indication for the risk of disturbance of the natural cycle is to compare the respective magnitudes of the economic and the ecological inputs. Relatively large economic inputs then constitute a large risk for disturbance of the natural cycle by unwanted or unavoidable losses. On a global level, this type of comparison has been made (Schlesinger, 1988): the conclusion is that human intervention has doubled the total global nitrogen fixation. Eventually, most of this extra nitrogen ends up in the environment, threatening to disrupt the natural cycle. In this case, the measure has been the industrial N-fixation compared to the biological fixation. On a national level, import and export both in the economy and in the environment complicate the case. The comparison then could be made on the basis of anthropogenic versus natural *use*.

### *Interpretation for environmental policy*

For both calculation procedures of the indicator, a higher figure indicates a larger disruption risk. A standard, based on an 'allowable' emission, is missing. A zero disruption risk may serve once more as an ideal, never to be reached reference value. For metals, this indicator has little relevancy.

## 5 Discussion and conclusions

Below, the twelve indicators described above are summarized. In the table is indicated

- whether or not the indicator can be linked to a "sustainable" level, i.e. a reference value
- what information the indicator provides on the state of the flows and stocks and the changes therein
- what information the indicator provides regarding the shifting of problems
- whether or not the indicator provides a direction for the management of the substance.

	<i>reference value<sup>1</sup></i>	<i>information on state &amp; changes</i>	<i>type of early warning &amp; problem shifting</i>
<b>ENVIRONMENT</b>			
1. concentration	standards	pollution	
2. daily intake	standards	pollution	
3. environmental accumulation	0	pollution	time
4. total emissions	targets; 0	pollution	
5. depletion rate	0	depletion	location
<b>ECONOMY</b>			
6. efficiency	100%	economic management	
7. use level	-	economic management	
8. recycling rate	100%	economic management	
9. economic accumulation	0	economic management	time
10. economic dissipation	0	economic management	time
<b>SYSTEM</b>			
11. pollution export	0	pollution	location
12. disruption rate	0	disruption	time

<sup>1</sup>Reference values such as "0" or "100%" indicate that no targets have been set by environmental policy, and that common sense or common agreement indicates that "less is better", or in some cases "more is better". Sometimes, it will not be possible to set standards or targets while in other cases it would be possible but has not been done so far.

Referring back to Chapter 1, the first question to be discussed concerns the completeness of the set. Are all relevant aspects covered? The set is designed to cover both sustainable development and environmental quality. Indicators 1 - 5 refer to the environment and our interference with it, and therefore can be stated to address environmental quality. Indicators 6-12 are about the societal metabolism and therefore are related to (sustainable) development. As stated in Chapter 1, the "sustainability" aspect should be covered by defining for both environmental and economic indicators a sustainable level as a reference value. From the above, it has become apparent that such reference values are at present very rare: they exist only for the concentrations in the environmental compartments and for the daily intake by humans. For some of the other indicators, more specifically for the environmental ones, it would seem to be possible to define substance-specific reference values, provided the necessary knowledge regarding fate and degradation is available. For others this is not possible, at least not without a number of specific additional assumptions. For example, a "sustainable" use level cannot be defined without having information

regarding production processes and waste management practices, in other words, is very much dependent on technology assumptions. Such indicators therefore only can be used in a relative sense, to compare different regimes ("less is better"), or they can be used to derive management options (efficiency boost vs volume policy, for example).

From the table above it can be concluded that the set provides information on the state & changes of flows and stocks of a substance, on problem shifting and on early warning. As a general set, it seems fairly complete, of course within its intrinsic limits: the one substance chain within the one region. It is likely that - depending on the goal of a study and the specific system's definition derived from that goal - additional indicators are required for specific purposes. The concentration indicator thus could be specified for parts of the region instead of averaged for the total region. The accumulation indicator could be detailed further for different economic sectors (construction) or economic stocks (copper in water pipes). The same could be done for the efficiency indicator if this is helpful to the goal of the study, or for still other indicators. This however would not lead to an expansion of the set of indicators, but to an optional further detailing.

The second question then is, whether the indicators are mutually exclusive. This question is more difficult to answer. The overview of flows and stocks is obtained by relating all flows in the system to each other. Thus, the input of the system is linked to the output by the law of mass conservation. The efficiency of processes and the emissions from those processes are closely related. The concentration and daily intake indicators are also closely linked: the daily intake is calculated from the concentration in the various environmental compartments. However, to exclude either the daily intake or the concentration leads to loss of information: the daily intake does not inform us on other consequences of the presence of the substance in the environment, but the information on human health is much more directly meaningful. A further refining of the set may be necessary in due time. For now, deleting one or more indicators from this list leads to its being incomplete, i.e. its not covering all relevant aspects of a substance chain regime.

The question whether some of the indicators are in fact superfluous cannot be answered in a straightforward manner. This depends on the goal of the study, but also on the chosen type of quantification. If a comparative static approach is chosen, wherein the steady states of different regimes are calculated, the accumulation indicators become irrelevant since no accumulation takes place. When stock data are available and dynamic modelling is used to quantify the overview, the environmental accumulation can also be translated into concentrations directly and therefore would be superfluous. Some of the indicators certainly are related to each other in some way, for example efficiency and recycling rate: the larger the recycling rate, the higher the efficiency will be as a rule. However this is not a straightforward one-to-one relationship. Application in practice may serve to philter out such correlations and may lead to alterations of the list of indicators in due time.

The last question may be, whether the indicators provide sufficient information for defining a substance management strategy. Some directions certainly can be distilled from the set, for example, whether a further increase of efficiency or a boost of recycling is still possible or not. More directly relevant information however can be derived from the origins analysis as described by Van der Voet et al. (1995b): the contribution of the various sources to specific environmental problem flows. This origins analysis points directly at the immissions, sectors and systems inflows that must be regulated in order to solve a specified problem. The set of indicators cannot replace this origins analysis. The use of this set is limited to the evaluation of the overview of flows and stocks. It is however possible to compare different regimes with the indicators. This, too, is relevant for the definition of a management strategy: the insight in the usefulness and problem solving potential of certain abatement measures.

Such a set, if worked out and tested properly, can be used to evaluate the current situation as well as the future consequences of a substance management regime (the current regime or a modified one). This may provide adequate information regarding a region's substance management from a "physical economy" point of view. It should be kept in mind that this point of view does not address all relevant issues. Monetary considerations are wholly out of the picture. Problem-shifting to other substances will not become apparent, nor will changes in energy use or environmental damage by physical interventions. Moreover, even within the scope of a region's substance management there is the problem of weighing contradictory indicators: in such cases, which indicators must prevail? Ultimately, this may well be a subjective matter which cannot be answered scientifically. Do we prefer a cleaner environment now at the possible expense of the future? Is it acceptable to locate our waste processing in other countries? This indicates the need for a weighing procedure of the indicators against each other (Janssen & van Herwijnen, 1994; Kortman et al., 1994, Anonymus, 1994). Possibilities for doing so are, for example

- prevalence of the indicators which can be linked to a reference value as the only ones allowing absolute judgment, combined with a "distance to target" or a similar approach
- establishment of an order of importance for the indicators
- appointment of weighing factors to the indicators
- development of an evaluation procedure wherein different possibilities may be tried out to establish the consequences of certain choices.

This last option seems most interesting, not only from the point of view of the possibility to be able to compare different regimes, but also from the point of view of identifying the consequences of societal choices and preferences in formulating a preference for one regime or another.

The final conclusion is, that it seems to be possible and useful to translate the overview of flows and stocks as delivered by an SFA study into a limited set of indicators, which as a group provide a measurement of the situation in terms of environmental quality and sustainable development. On certain points, especially the mutual exclusiveness of the indicators, a further refinement is required. With this set, it is also possible to compare different substance management regimes. The main remaining problem is the weighing of the indicators against each other.

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## Appendix 1: Definition of nodes, flows and stocks

In this appendix the various categories of stocks, flows and processes and the various types of flows and processes are defined. This definition work is necessary for the indicators applied in this report and for a standardized report of results.

For each item a definition and an example is given and it is stated whether the category or flow/process type is relevant for metals; the distinct categories and types have thus a potential broader meaning than just for metals. (Categories and flow types have been summarized before in figure 2.)

### Stock categories

#### Immobile stocks

*Definition:*

Stocks that under the given environmental conditions on a human time-scale (as opposed to geological time scales) do not circulate in or interact with the economic or environmental flows and stocks, nor are influenced by economic or environmental processes.

*Example:*

Geological stocks can be classified as immobile. This category may also encompass economic stocks, if sufficiently isolated from both economic and environmental processes. Immobile stocks are considered as sinks for the system under study.

*Relevant for metals:*

yes.

#### Mobile stocks

*Definition:*

Stocks that under the given environmental conditions can circulate in or interact with the economic or environmental flows, and can be influenced by economic or environmental processes.

*Example:*

Environmental: The total amount of substance studied in the soil of a given region.  
Economic: The total amount of substance studied in batteries in a given region.

*Relevant for metals:*

yes.

### Flow categories

#### Import

*Definition:*

Substance flows entering the system studied from a neighbouring system.

*Example:*

Environmental process: Transboundary inflows via air or surface water, e.g. the inflow of chemicals into the Netherlands from Germany and Switzerland through the Rhine.

Economic process: Transboundary inflows of tradable items from abroad, e.g. cars.

*Relevant for metals:*

yes.

#### Export

*Definition:*

Substance flows leaving the system studied to a neighbouring system.

*Example:*

Environmental process: Transboundary outflows via air or surface water, e.g. the outflow of chemicals to the North Sea from the Netherlands through the Rhine.

Economic process: Transboundary outflows of tradable items to abroad, e.g. cheese.

*Relevant for metals:*

yes.

### Accumulation

*Definition:*

Increase in one or more of the available mobile stocks of a substance in the system.

*Example:*

Environmental process: accumulation mainly occurs in soils and sediments, in the groundwater, and in standing stocks of biota.

Economic process: accumulation occurs in an increasing amount of used products (e.g. batteries), which are produced or imported but not discarded in the same time period (e.g. one year).

*Relevant for metals:*

yes.

### Desaccumulation

*Definition:*

Decrease in one or more of the available mobile stocks of a substance in the system (outflow of stock surpasses inflow).

*Example:*

Environmental process: leaching from the soil's stock.

Economic process: discarding of old (i.e. at present out of production) products.

*Relevant for metals:*

yes.

### Mobilisation

*Definition:*

Entering of substances into the environment or economy from the system's immobile stocks.

*Example:*

Environmental process: Flow from geosphere to environment (erosion).

Economic process: Flow from economic immobile stocks to economic activities (mining, extraction).

*Relevant for metals:*

yes.

### Immobilisation

*Definition:*

Disappearing of substances from the environment or economy to the system's immobile stocks.

*Example:*

Environmental process: Flow from environment to geosphere (sedimentation to deeper layers).

Economic process: Flow from economic activities to economic immobile stocks (putting wastes back to the mines; long-life (ages) application in e.g. some kinds of building materials, or in slag from which emissions can occur by corrosion). *Note* that (im)mobilisation is not the same as (des)accumulation: (im)mobilisation is about immobile stocks while (des)accumulation is about all other (mobile) stocks.

*Relevant for metals:*

yes.

### Extraction

*Definition:*

Substance flow from the environmental domain to the economic domain of the total system studied.

*Example:*

Extraction of bauxite containing aluminium.

*Relevant for metals:*

yes.

### Emission

*Definition:*

Substance flow from the economic (sub)system to the environmental (sub)system.

*Example:*

Flow of SO<sub>2</sub> from a car to the air due to the burning of fuels.

*Relevant for metals:*

yes.

### Throughput

*Definition:*

Flow from economic process to economic process or from environmental process to environmental process *within* the system studied.

*Example:* Aluminium produced by Hoogovens to the car producing industry, both within the Netherlands (in an SFA on aluminium in the Netherlands in 1990).

*Relevant for metals:* yes.

### Flows

#### Final waste

*Definition:* Those wastes which will be landfilled. As a default, final waste is considered to be a flow within the economy, and only the emissions from the landfill are considered as flows to the environment. (Waste to an incinerator is thus not considered as final waste, since the slag from incineration can be applied in road building and are then considered as non-functional recycling; idem compost).

*Example:* Household waste to landfill, etc.

*Relevant for metals:* yes.

#### Non-functionally in recycled products, materials, wastes etc.

*Definition:* Collecting and dismantling or granulating of disposed product/material for new applications, in which the substance has no function but only is a contaminant.

*Example:* Application of (substances, e.g. metals in) disposed building materials in road building application.

*Relevant for metals:* yes.

#### Functionally recycled as substance or in products, materials, wastes etc.

*Definition:* Collecting and dismantling or granulating of the substance studied from the disposed product/material which contained the substance, for a new application of the substance in the same or another product/material.

*Example:* Application of aluminium of beer cans in motor blocks for cars; collection and re-use of milk bottles.

*Relevant for metals:* yes.

#### Non-functionally in products, materials, wastes etc.

*Definition:* Tradable items containing the substance studied as a contaminant.

*Example:* Cadmium in zinc gutters, cadmium in phosphate fertilisers etc.

*Relevant for metals:* yes.

#### Functionally as substance or in products, materials, wastes etc.

*Definition:* Tradable items containing the substance studied as a contaminant.

*Example:* Aluminium as material, aluminium in window frames, cadmium as pigment in plastics, aluminium in disposed aluminium liquor cans etc.

*Relevant for metals:* yes.

### Air

*Definition:* Environmental medium mainly consisting of an oxygen and nitrogen gas mixture which surrounds the earth everywhere and is indispensable for organic life.

*Example:* The air above the Netherlands.

*Relevant for metals:* yes.

### Water

*Definition:* Environmental medium consisting of H<sub>2</sub>O molecules which is liquid, spread all over the earth and indispensable for most forms of organic life.

*Example:* The Rhine.

*Relevant for metals:* yes.

### Soil

*Definition:* Environmental medium including a part of the upper part of the earth crust with differing properties from the underlying stone.

*Example:* Clay soil, loam soil, etc.

*Relevant for metals:* yes.

### Sediment

*Definition:* Environmental medium which can best be indicated as the underwater soil, which is continuously newly formed by sedimentation of particulate matter in water.

*Example:* The sediment of the Rhine.

*Relevant for metals:* yes.

### Groundwater

*Definition:* Environmental medium which includes the water under the soil.

*Example:* Groundwater as a source for drinking water; leaching of metals in soil to groundwater.

*Relevant for metals:* yes.

### Sea

*Definition:* Environmental medium consisting of H<sub>2</sub>O molecules and salt, which is liquid, spread all over the earth and the medium of many forms of organic life.

*Example:* The North Sea.

*Relevant for metals:* yes.

## Process categories

### Node

*Definition:* Point of redistribution of substance flows.

*Example:* A separate post in the substance account representing a (group of) process(es). A node has at least three attributes: sector, technology and location. To every node, one or more, mutually related, inflows and outflows of metals can be linked and accumulation can take place within the node.

*Relevant for metals:* yes.

### Sink

*Definition:* Node with an inflow from other nodes within the system but with no outflow to other nodes within the system.

*Example:* Sinks can be classified as export, transboundary outflow, immobilisation by economic or environmental processes, and chemical degradation by economic or environmental processes.

*Relevant for metals:* yes.

### Source

*Definition:* Node with an outflow to other nodes within the system but with no inflow from nodes within the system.

*Example:* Sources can be classified as import, transboundary inflow, mobilisation by mining or erosion, and chemical forming by economic or environmental processes of a substance.

*Relevant for metals:* yes.

### Processes

#### Economic process

*Definition:* Human controlled unit transforming inputs into economically valuable outputs, such as products, materials, components, or into economically valuable services such as transport and waste management.

*Example:* The production of steel.

*Relevant for metals:* yes.

#### Environmental process

*Definition:* Nature controlled unit transforming inputs into outputs without any economic value.

*Example:* The degradation of DDT into DDE.

*Relevant for metals:* yes.

## ERRATA

Ester van der Voet, Jeroen B. Guinée & Helias A. Udo de Haes (1997): "Indicators for integrated substance chain management", CML report 139, Leiden University

The lines are counted without blanks, i.e. only lines containing text are counted.

Page 5	line 24:	replace ".. outcomes of .." with ".. outcomes if .."
Page 11	line 9:	replace "Three measures .." with "Five measures .."
Page 11	line 21:	replace "(see Ad 3.)" with "(see Indicator 3)"
Page 14	line 4:	replace ".. Section 2.2, .." with ".. Section 3, .."
Page 14	line 5:	replace ".. have been .." with ".. are .."
Page 14	line 15:	replace "In section 3.2 .." with "In Section 3.1 .."
Page 14	5th line from bottom:	replace "(see indicator 5)" with "(see indicator 7)"
		replace "(see indicator 6)" with "(see indicator 8)"
Page 15	line 6:	replace ".. indicator 6" with ".. indicator 8"
Page 18	line 17:	replace "(see also Table 1)" with "(see also Table 3)"
Page 22	line 1	delete $-\sum_{i=f}^k F_{\text{emission}, i}$ from formula
Page 32	3rd line from bottom:	replace "(see indicator above)" with "(see indicator 4)"
Page 33	lines 18 and 19, note 5 with Table 4	replace ".. reference leakages .." with ".. footprint leakages .."