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Substances from cradle to grave : development of a methodology for the analysis of substances flows through the economy and the environment of a region: with case studies on cadmium and nitrogen compounds

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SUBSTANCES FROM CRADLE TO GRAVE

Development of a methodology for the analysis of substance flows through the economy and the environment of a region

with case studies on cadmium and nitrogen compounds

PROEFSCHRIFT

ter verkrijging van de graad van Doctor
aan de Rijksuniversiteit te Leiden,
op gezag van de Rector Magnificus Dr. L. Leertouwer,
hoogleraar in de Faculteit der Godgeleerdheid,
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The thrushes sing as the sun is going
and the finches whistle in ones and pairs
and as it gets dark, loud nightingales in bushes
pipe as they can when April wears,
as if all times were theirs.

These are brandnew birds of twelvemonth growing
which a year ago, or less than twain,
no finches were, nor nightingales, nor thrushes,
but only panicles of grain
and earth, and air, and rain.

Thomas Hardy.

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PREFACE

The research on behalf of this thesis has been carried out at the Centre of Environmental Science, Section Substances & Products, during the period 1991-1995. The subject, Substance Flow Analysis, has become one of the two main focuses of the Section, the other focus being product Life Cycle Assessment. The main part of the investigations has been conducted within the framework of a PhD project financed by the Dutch Foundation for Scientific Research (NWO). Research projects on behalf of The Netherlands' Ministry of Housing, Spatial Planning and Environment and of the Province of Zuid-Holland, and a subsidy from the Central Bureau of Statistics, have also contributed to the results. Apart from myself, a group of four researchers of the CML Section Substances and Products has been involved in this work during the whole four year period. Other members of the Section Substances & Products also have made contributions. Finally, student research by Lipkjen van Egmond and by the CML interdisciplinary student groups of 1989, 1991 and 1992 has been very important for the results as they are presented here.

It was possible to conclude the work on this thesis within this rather limited period of time only by the consideration my family has had with me, as well as my colleagues, who have contributed greatly by taking over my daily tasks during the first half of 1995, so I could concentrate on finishing this PhD research.

SUMMARY

The aim of this thesis is to contribute to the development of the analytic tool of Substance Flow Analysis (SFA). The general aims of this tool are discussed in Chapters 1 and 2: SFA aims to provide relevant information for a region's overall management strategy with regard to one specific substance or a limited group of substances. In order to do this, a quantified relationship between the economy and the environment of a geographically demarcated system *a* established by quantifying the pathways of a substance or group of substances in, out and through that system. SFA can be placed in the scientific field of *industrial ecology*, as one way to operationalize the concept of *industrial metabolism.* In this concept, an analogy is drawn between the economy and environment on a material level: the economy's "metabolism", in terms of materials mobilization, use and excretion to create "technomass", is compared to the use of materials in the biosphere to create biomass. The economy thus is viewed only in terms of its materials flows.

The policy area most closely related to this concept is *integrated chain management.* Economic chains from cradle to grave are the subject of regulation. The "integrated chain" can be defined in different ways, each with its own corresponding analytic tool. The substance chain is, of course, the relevant one for this thesis. Other chains are, for example, the product chain with its tool product Life-Cycle Assessment (LCA), or materials chains and Materials Flux Accounting (MFA). Substance policy and the potential role of SFA supporting the formulation of such policy are discussed next. Here, not only the possibilities, but also the limitations are relevant. A first limitation is linked to the view of the economy in physical terms only. SFA does not provide information about costs and other economic or societal aspects. Although such aspects may be pan of the SFA input, they never can be an output. A second limitation is the narrowing down of the picture to the one substance (group). Problem shifting to other substance chains therefore cannot be investigated with this tool.

This thesis aims to contribute to the field of SFA in two directions: the development of SFA methodology (Part II), and making explicit the role of SFA supporting substance policy (Part ffl). Research on these two issues has been conducted simultaneously. Methodology development benefits from testing the theories in practical applications. On the other hand is it important, that developed methodologies are indeed applicable in practice. In Part IV, two case studies are worked out: cadmium and nitrogen compounds, both on the level of the European Union.

The SFA methodology (Part II)

In Chapter 2, a general framework is presented for materials and substance flow studies. This framework can be the starting point for a general discussion addressing the question of which choices consequently have to be made, how those choices may be affected by the aim of the study to be conducted, and what are the implications for the conclusions that can be drawn by policy makers. The framework is composed out of three steps:

1. definition of the system
2. quantification of the overview of stocks and flows
3. interpretation of the results.

The *system's definition* is closely linked to the definition of the integrated chain that is being studied. It primarily has to do with specifying the four basic variables: substance, space, time, and functions. Those basic variables determine the system to its main characteristics. In Chapter 2, the definition of the SFA system, the integrated substance chain, starts from the choice for a substance or a limited group of substances. The system is furthermore determined with regard to space (a

region), and time (one year), but encompasses all functions or applications of the substance.

A further specification can be made by the identification of subsystems, the categorization of flows and stocks, and the identification of processes to include within the system. Distinguishing subsystems is not required to obtain the overview of flows and stocks, but is closely linked to the interpretation of the results. Generally, two subsystems are distinguished: the societal subsystem (economy, technosphere, anthroposphere), and the environmental subsystem (environment, biosphere). This makes it possible, for example, to speak of "emissions" as border crossings between one subsystem and another. The geosphere or lithosphère could be defined as a third, separate subsystem. Both, or all three, can be subdivided further, depending on the requirements for interpretation. The definition of subsystems always leads to practical problems, which must be solved in a practical manner.

In the SFA system's definition, the categorization of the inflows and outflows is made in comparable terms for the economy and the environment, following from the industrial metabolism view of the biosphere/technosphere analogy.

A final important issue is the definition of the system's economic and environmental processes. These processes in fact determine the substance's pathways. The level of aggregation on which to define these processes is strongly dependent on the scale level of the analysis.

It is important that the system's definition be made explicitly regarding the above mentioned aspects. Precisely how these definitions should be made depends on the specific SFA application involved (see below).

For the *quantification of the overview of stocks and flows,* three possibilities are identified:

- bookkeeping: keeping track of flows and stocks afterwards by registering them, thus enabling policy makers to spot trends, and to evaluate the effects of certain changes including policy measures;
- static modelling: specifying the relations between stocks and flows, thereby enabling policy makers to trace the origins of pollution problems on the one hand, and estimating the effectiveness of measures on the other;
- dynamic modelling: including time as a modelling parameter, thereby making it possible to predict situations for specific future years.

There is no "best" choice: each type of modelling is useful, each has different functions for supporting environmental policy, and each has different data demands and different requirements for the exactness of the outcome. This last point is especially relevant for the choice of static or dynamic modelling: with dynamic modelling, the outcome is a prediction of the future, which must be more or less accurate in order to be able to serve as a basis for policy decisions; with comparative static modelling, the outcome is an indication of the general usefulness of certain measures *compared to others,* not pretending to predict and therefore obviously excluding many uncertainties. Table S.1 summarizes the possibilities for application of the three modelling types.

When setting up a quantification system, further decisions must be made regarding

- which variables to choose as the system's fixed variables (physical or economic causality)
- which variables to appoint as the balancing items
- how to derive the distribution coefficients
- whether or not to include the system's stocks in the quantification procedure.

Apart from practical considerations, for example regarding the availability of data, the specific SFA application determines these choices. This aspect is discussed in Chapter 5.

Table S.1 Modelling techniques and their possible applications

type of modelling / application	bookkeeping system	static modelling	dynamic modelling
signalling	+		
spotting trends	+		
evaluation ex post	+		
origins analysis		+	
comparing regimes		+	
evaluation ex ante		+	+
extrapolating trends			+
making predictions			+
scenario analysis			+

Regarding the *interpretation of the SFA results,* two approaches have been examined in Chapter 4: the direct evaluation of the flows and stocks as they present themselves from the overview, and the definition of indicators for integrated chain management.

Possibilities to evaluate the overview of flows and stocks directly, without additional information and without further calculations, are limited but nonetheless important. A summary of a region's overall substance regime can be sketched with the help of the Substance Flow Diagram, pictured in Chapters 2, 4, 7, and 8. By drawing a picture of a substance's life cycle, a first rough insight is provided into the size of the economic cycle and the leaks from it in an absolute as well as relative sense, and therefore some first general recommendations for a substance management strategy.

With regard to the environmental flows, more detailed information can be extracted from the overview with the help of additional information regarding the harmful qualities of the substance. By introducing either concentration (stock) or emission (flow) related environmental standards, the environmental stocks and flows out of the SFA overview can be translated into transgressions. The use of equivalency factors, borrowed from the product LCA impact assessment, provides possibilities to compile large groups of substances into one analysis. This last procedure also has its drawbacks, however: information is lost with regard to the actual problems occurring within the region. For the analysis of current problems related to the substance under study, the origins analysis as described in Chapters 3 and 5 provides good possibilities (see below, Part III).

No policy standards, limits, or targets exist for the economic flows. However, it certainly would be useful to be able to comment on the economic substance flows as the instigators for the environmental flows. This could then serve either as an early warning, or as a recommendation for environmental policy. The use of indicators is proposed to evaluate the economic substance regime. In Chapter 4, an attempt has been made to define a comprehensive set of indicators for this purpose:

Depletion

- *virgin input:* total economic virgin input of the substance (not worked out here separately, but part of Indicator 3, primary/secondary materials use)
- *resource depletion:* contribution of the region to (global) depletion of mineral resources, absolutely and per inhabitant (not worked out here)

Pollution

- ***pollution problems:* occurrence of pollution within the region: selected flows (emissions or environmental flows) set against regional environmental quality standards or targets (as worked out in 4.3, and also in the case of nitrogen, chapter 8)**
- ***totalized losses:* totalized emissions from the economic chain/cycle (not worked out here)**
- *disturbance risk:* risk of the economic cycle disturbing natural substance cycles (worked out in 4.4.4, economic vs. natural cycle)
- *surplus:* pollution caused by the region: contribution of regional emissions to fluvial, continental or global pollution problems, absolutely and per inhabitant (example discussed in 4.4.2: mineral surplus. Also in 4.3: introduction of problem causing potentials)

Management

- *efficiency:* efficiency of economic substance life-cycle (worked out in 4.4.3 as efficiency of life-cycle stages and as primary/secondary materials use)
- *final use:* totalized economic use: either flow or stock (not worked out here)
- *recycling:* recycling percentage (worked out in 4.4.3, indicator no. 3)

Problem shifting

- *within the area:* the chance of policy measures not working out as expected (worked out in 4.4.3, the non-intentionality indicator)
- *to the future:* accumulation in the environment and accumulation in the economy (worked out in 4.4.2 and 4.4.3)
- *to other regions:* global shift - pollution/depletion in region versus pollution/depletion caused by region (worked out in 4.4.3, the pollution export indicator)

Such a set, if worked out and tested properly, can be used for evaluating 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 cover all relevant issues. Moreover, even within the scope of a region's substance management, there is a problem of giving proper weight to the various indicators: if contradictory, which of the indicators are most influential? Ultimately, this may well be a subjective maner 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? These are the questions that enter into the subjective analysis. This problem of proper weighing of the indicators is pressing indeed if the aim is to integrate the set of indicators into one value or index for the integrated environmental risks of an economic substance chain regime. In this thesis, no attempt is made to do so. In the future, however, this will almost certainly return as an important issue.

The use of SFA for an integrated substance chain policy (Part III)

SFA has been developed as an analytical tool. The main policy supporting possibilities therefore lie in the field of the *analysis* of current environmental problems and of the consequences of

considered abatement measures. Additionally, SFA can play a role in the *design* of substance management strategies.

The analytic SFA applications

Five analytic SFA applications are distinguished in Chapter 5. Each of these applications has different requirements from the SFA system's definition, the appropriate type of modelling, and the definition of the variables within the quantification system.

1. *state:* the evaluation of the present situation in a region. This SFA application can be defined as a monitoring activity: keeping track of the region's substance flows, and their actual developments through time. This application provides information on current problems and trends. The influence of past developments and policies becomes apparent. The major flows responsive to regulation can be identified.
2. *footprint:* the (worldwide) environmental consequences of the consumption in a region. This SFA application enables policy makers to view the consequences of the consumption or final use of the substance by the population of their region outside the regional borders. It can also be used to spot problem shifting to other areas when contemplating alternative regimes. In Chapter 4, an indicator is defined for this type of problem shifting.
3. *origins:* the economic or environmental causes of pollution problems in a region. The origins analysis provides an insight in the causes of any specific problem flow on three levels: the direct causes, the economic sectors responsible, and the ultimate origins at the inflow border of the system. This provides a useful base of information for the solution of those problems.
4. *solutions:* the comparison of different substance management regimes on their environmental consequences. This option provides an insight into the consequences - both the effectiveness and the possible problem shiftings - of certain abatement measures or regime changes. This option, based on comparative static modelling, can be used to appraise general trends for possible solutions. It cannot be used for an evaluation in an absolute sense.
5. *predictions:* the prediction of a future situation under certain assumptions. This option is the most elaborate one, since it involves dynamic modelling. If operational - which it is not at present - it can be used for scenario analysis and for an absolute evaluation of regimes, i.e. determining whether in a specific future year the policy targets will be met under certain assumptions.

The design of substance management strategies

The development of substance management strategies is the subject of Chapter 6. The aim was to establish whether it would be possible to use general, easily available information about a substance as a basis for a substance management strategy. If so, this could imply a profound streamlining of substance policy. In Chapter 6, economic substance characteristics are formulated, based on physical/chemical and other substance properties on the one hand and on qualitative data related to the economic applications on the other hand. These economic characteristics can be used to draw conclusions regarding the principle usefulness of general abatement measures in each specific case.

Economie substance characteristics are categorized in three groups:

functional characteristics	resource and material charact.	intentionality characteristics
substitutability	depletability	intentionality of recovery
dispensability	renewability	intentionality of formation
	synthesizability	intentionality of use
	concentration	
	recoverability	
	waste/emissions ratio	
	degradability	

A protocol is outlined that could be used to obtain a first rough draft for any specific pollutants policy. In this protocol, a list of ten general abatement options is confronted with the economic characteristics of the substance, in order to establish, in principle, the usefulness of the abatement options. Out of the useful options, a strategy outline can be built. The options are defined as follows:

1. prevention of recovery or formation
2. extraction of pollutants from the main material
3. closing process leaks in a technical sense (including increasing process efficiency)
4. terminating use or application (if necessary including substitution by another substance)
5. recycling a: collection and product re-use (depending on product, not substance characteristics)
6. recycling b: collection, substance recovery and substance re-use
7. recycling c: re-use of products of waste management processes (compost, fly ash, sludge etc.)
8. waste management a: collection and landfill
9. waste management b: collection and degradation (possibly but not only by incineration)
10. waste management c: collection and immobilization.

The general management strategy outlines for cadmium and nitrogen compounds, as put down in Chapter 6, are sketchy. However, the general outlines have the distinct advantage of being comprehensive (including all stages of the economic life cycle), and appear to avoid more and less obvious problem shifting mechanisms. On a general level, they make sense and therefore may serve as guidelines for a more detailed substance management measure package. It seems possible, therefore, to make the connection between general, easily available substance data and the main directions for its management. It may even be possible to include large groups of substances, that have similar economic characteristics, in a general strategy. However, the idea of economic characteristics has not yet developed beyond the conceptual stage. More thinking and, in due time, more research must be directed towards this notion in order to develop it further. To fill in the details of a strategy, more information is required. An SFA study is not always needed, but is strongly recommended for substances with complicated pathways or an extended stay in the economy.

The case studies (Part IV)

As stated above, two case studies have been conducted, cadmium and nitrogen, both on the level of the European Union. The results are presented in Chapters 7 and 8. The case studies served primarily to facilitate methodology development, but relevant conclusions could also be drawn from the case studies themselves. The main SFA applications in these case studies have been the *state*, the *origins* and the *solutions* applications. The results of these applications have been used to outline a management strategy for the substances involved.

Cadmium

The economic production and use of cadmium in the EC leads to severe environmental problems. Based on a substance flow analysis, the following problem flows have been identified, in increasing order of manageability:

- agricultural soil load
- surface water load
- landfill sites
- economic accumulation.

A variety of direct causes can be identified for these problem flows, and responsibility can be traced back to a limited number of economic sectors. These sectors are the same for each problem flow, but with different contributing sources in each case. Ultimately, the Cd flows can be traced back to two main economic inflows: the import of phosphate rock and the import or extraction of zinc ore. Zinc ore is the main source of the intentional applications of Cd, which end up mostly on landfill sites or accumulating in the economy. In phosphate rock Cd occurs as a contaminant, polluting the most important P-product: fertilizer, and causing Cd to circulate in the economic-environmental agricultural system.

For a successful cadmium policy, the generally accepted notions of source-oriented policy and recycling appear to have to be amended in this special case. The EC policy, according to the proposed lines of (1) end-of-the-pipe measures, (2) a phase-out of certain applications, and (3) recycling of batteries and plating, conforms to those notions. Various forms of problem shifting are expected to appear:

- diffuse emissions will be replaced by local emissions
- emissions within the EC will be replaced by emissions outside the EC
- current emissions will be replaced by emissions at a later date.

This policy does not appear to offer a sustainable solution to the cadmium problem, mainly because it does not consider the inelastic nature of cadmium supply, that is, primarily as a by-product of zinc.

In order to be effective, a cadmium policy must take into account the way Cd enters and filters through the economic system. On the inflow side, measures must be directed not at Cd but at the main products, zinc and phosphate. Otherwise, Cd-oriented measures such as battery recycling only lead to increased Cd availability and thus to potentially larger future losses to the environment. On the outflow side, collection of Cd-containing waste and products and subsequent safe storage in a concentrated form seem to offer the best solution both from a pollution and from a depletion point of view. To a certain extent, these conclusions can be generalized to other substances. All ore contaminants, recovered wholly or mainly as a by-product of other materials, will exhibit more or less the same behaviour. Substances occurring as a contaminant in products will require a different policy from intentionally applied materials. Still more generally, characteristics related to economic supply and demand such as intentionality of recovery and intentionality of use may be an indispensable basis for a successful substance-oriented policy.

Nitrogen compounds

Various environmental problems related to nitrogen compounds occur at various scale levels. These problems have been analyzed comprehensively by describing and modelling the EC as a system of interdependent nitrogen flows. Although the immediate causes of the separate nitrogen related problems vary a great deal, three selected problem flows can be traced back to the same ultimate origins. The atmospheric deposition of gaseous N-compounds, the leaching of nitrates to groundwater, and the anthropogenic input of N into the North Sea can all be attributed mainly to the import and production of fertilizer. The food production and consumption sectors can be viewed as the sectors most responsible for nitrogen-related problems. Although the problems

occur on various scale levels, the most important causes are regulated on the EC level: the EC Common Agricultural Policy (CAP).

Measures and policies to combat nutrient-related problems are formulated by various Member States as well as by various international bodies. The most important international measures are formulated in the EC Nitrate Directive, and in the INSC agreements and ParCom proposals for the protection of the North Sea. The changes in the CAP according to the McSharry Plan appear not to affect the agricultural nitrogen flows in a significant manner. The environmental problems are thus not so much related to overproduction, but to the CAP goal of self-sufficiency itself.
Most measures under the various existing policies and agreements are of a technical, end-of-the-pipe nature. If these are implemented adequately, two of the three selected problem flows are expected to decrease significantly but in neither case sufficient to solve the problem according to the accepted environmental goals. The third problem flow, the leaching of nitrates into groundwater, will remain wholly unresolved. This is due to the fact that the most important origins, the nitrogen flows in agriculture and ultimately the addition of nitrogen to the system in the form of industrial fertilizer, are not significantly influenced.

To adequately solve all three nitrogen-related problems, therefore, other measures will be necessary, and are conceivable. Phasing out the import of agricultural products for use as fodder from outside the EU appears to have only a minor impact on the environmental problems related to nitrogen compounds. Depending on the specific assumptions, the changes may be either slightly for the better or slightly for the worse. An extreme technical program, including air emission reduction by 90%, treatment for all industrial and household wastewater, and centralized manure treatment for 25% of all animal manure, could solve two of the three problems. However, the problem of nitrates leaching into the groundwater would in all likelihood remain largely unresolved. Resolution of the groundwater problem therefore appears to be incompatible with EU agriculture as it now exists, and will require radical measures in the agricultural sector. Two possible directions have been examined by calculating the impacts of two such extreme policies: (1) returning agriculture to the pre-fertilizer age by banning the use of fertilizer, and (2) increasing agricultural efficiency by the one radical option that is possible, the elimination of livestock production altogether. Both options seem effective: the first through reducing the agricultural nitrogen cycle as a whole to a tenth of its current throughput, and the other by tripling agricultural efficiency. However, the implications of such extreme measures for society would be severe. In the one case, agricultural output is reduced to a tenth of the current level as well, making the EU largely dependent on imported food, while at the same time shifting the environmental problems related to food production to other areas. In the other case, the adoption of a completely veganistic lifestyle by the EU population is implied. Apart from that, major parts of the agricultural sector would disappear in both cases.

Developing a solution for these problems within the EU implies dealing with a major clash between the economy and the environment. On the one hand, nitrogen compounds fulfil an indispensable function as nutrients. On the other hand, the environmental problems caused by food production and consumption are severe. Solving the concurrent environmental problems implies radical and possibly disruptive changes. It is then a question of choice: do we choose to solve the problems to the degree laid down in the various agreements, or do we choose to keep food production and consumption more or less as they are at present? For this moment, a proposal for increasing the environmental quality standard level of 50 mg nitrates/1 groundwater would represent an arguable case. For the future however, with an ever-growing world and increasing EU population, the changes in agricultural style and food patterns described above might have to be reconsidered. If a substantial increase in the efficiency of agricultural nitrogen use by technical means remains impossible, such changes may constitute the only option for solving the environ-

mental problems of the future.

General discussion, conclusions and recommendations

In Chapter 10, some general issues are discussed. These refer to
- the position of SFA in the field of integrated chain analysis
- **the further scientific development of SFA**
- **the potential for the use of SFA in support of environmental policy.**

The position of SFA in the field of integrated chain analysis

SFA has been developed as an analytic tool to support integrated substance chain management. As such, it has its possibilities but also its limitations. It is important to have a clear understanding of these limitations.

In the first place, SFA fills, or should fill, its proper role: as an analytical tool on behalf of the policy concerned with *integrated substance chain management.* No demands should be made of SFA that exceed its limitations. The two principal SFA limitations are the following:

1. The SFA point of view considers the world in terms of substance flows and stocks. Therefore, no outcome can be expected in other terms than those.
2. The SFA instrument is meant for use in substance policy. This means that one substance or a limited group of substances is being taken into account at a time. Problem shifting to other substance chains are therefore not apparent. To observe those shifts, other tools of integrated chain management, such as LCA or MFA, are more appropriate.

In the second place, there is the question of standardizing the SFA tool. So far, there has been little attention to harmonization of the efforts in this field. Steps towards harmonization require an agreement on two levels:

1. The relationship between SFA and other analytic tools in the field. In Chapter 1 it has already been stated that these tools have much in common. The development of the different methodologies therefore could benefit greatly if conducted in harmony, not only by spotting the differences but also by adopting similar procedures and even identical steps regarding a system's definition and modelling, if appropriate.
2. The SFA tool itself. The general framework, as it has been defined in Chapter 2, can be used for every SFA application. It would be an important step forward if agreement could be reached within the scientific community on such a general framework, on the choices that must be made within this framework, and on a procedure for making those choices for the different specific SFA applications.

Recommendations for a further development of the SFA tool

Regarding the SFA system's definition, the most important scientific discussion that must be entered into is the dependency that definition on the specific questions that must be answered by the SFA study. Much would already be clarified by separating the functional from the regional angle.

With regard to the quantification of the overview, there are several important issues:
- data availability and quality: for SFA applications on the level of EU member states, repairing the recent quality loss of the trade statistics is a matter that needs to be resolved. A second issue is the lack of data on economic and environmental stocks. Investigating these more carefully is strongly recommended in order to create one of the necessary conditions for evaluating potential future scenarios.
- modelling: attention to the development and implementation of dynamic substance flow

modelling is recommended, although it should be noted that its overall importance is somewhat put in perspective in this thesis. Another issue is the inclusion of economic causality in the modelling. As yet, economic causality is limited to the basic decision whether the model should be supply-driven or demand-driven. It would certainly be useful to try to put more of the economic laws into the model for the applications *solutions* and *predictions*.

- evaluation of the quantification step: the development of a standard procedure of sensitivity analysis, to be conducted for every case study, is recommended as well.

For the interpretation of the results, the link of the SFA outcome with existing evaluation systems, such as risk assessment models, or an evaluation procedure such as is used in some of the LCA studies, could be further worked out. In that way, the SFA results can be better interpreted by policy makers. Another recommendation is the further development of a set of indicators to characterize integrated chain management regimes, by which the degree to which the general goals of integrated substance chain policy are achieved can be measured.

Another direction of development concerns the linking of SFA to other types of models. Careful consideration is required to determine if, and how, such a step can be taken. On the input side, a link can be imagined with economic scenario models, where the output from the economic scenario model could be an input for an SFA model. On the output side, a link with existing environmental fate models can be considered, for example with a general multimedia model or with environmental models with a spatial dimension. Finally, the link to an economic evaluation system would be relevant, so that the physical changes could be matched with monetary changes. Adding this dimension would also open possibilities for optimizing measurement packages with regard to costs.

The value of SFA for environmental policy

In the case studies on cadmium and nitrogen, SFA has contributed especially by establishing a quantified connection between the economy and the environment. This has led to some new conclusions regarding the coherence of apparently separate environmental problems and the usefulness of abatement measures. The main contribution however has been on the totalized level, by making apparent the various mechanisms of problem shifting that go hand in hand with several types of solutions.

SFA applications that are recommended strongly for use in environmental policy are at present:

- the already existing *state* application for following the state of flows and stocks over the years
- the *origins* and the *solution* applications for identifying and testing options for a sound substance management strategy.

Both for *the footprint* and the *prediction* applications the outline is there, but the details must be filled in further before they can be used as standard options. It is very much in the interest of environmental policy to stimulate this further development of the SFA instrument. It is perhaps the only way that environmental policy can actually influence the direction of this development, and therefore the subsequent possibilities for their use of the tool.

A final observation is made in Chapter 10 regarding the need for simplification. It cannot be expected that extensive SFA studies will be performed regularly for all relevant substances. This, by the way, is also true for other analytic tools supporting integrated chain management: it will not be possible to perform LCA studies for all relevant products, nor risk assessment studies for every relevant situation. It is therefore important that both policy makers and environmental scientists involved in designing those tools also direct their attention to the task of streamlining

their use. This simplification may take various shapes:

- defining simplified versions of the tools
- defining general rules based on the patterns that arise out of the practical applications
- defining larger groups of substances to analyze within one framework
- indicating in which cases which tools are required, and in which cases policy can do without.

SAMENVATTING

Het doel van dit proefschrift is, een bijdrage te leveren aan de ontwikkeling van het analytisch instrument Stofstroomanalyse (Substance Flow Analysis, SFA). In Hoofdstukken 1 en 2 wordt het gebruiksdoel van dit instrument in algemene termen beschreven: het verschaffen van relevante informatie voor het opstellen van een beheersstrategie voor een bepaalde stof of stofgroep in een bepaald gebied. Om dit te bewerkstelligen wordt een kwantitatief verband gelegd tussen de economie en het milieu van een geografisch afgebakend systeem door een beeld te schetsen van de weg die de stof aflegt in, uit en door dat systeem. SFA behoort tot het wetenschappelijk veld van *industrial ecology*, als één van de mogelijke uitwerkingen van het begrip *industrial metabolism*. Met dit begrip wordt een analogie beargumenteerd tussen economie en milieu in fysieke zin: de "stofwisseling" van de economie, in termen van de mobilisatie, het gebruik en de excretie van materie teneinde "technomassa" te creëren, wordt vergeleken met de stofwisseling van de biosfeer voor het creëren van biomassa. Op die manier ontstaat een beeld van de economie uitsluitend in termen van stromen en voorraden van materie.

Het beleidsveld direct gerelateerd aan dit begrip is het *integraal ketenbeheer*. Integraal ketenbeheer reguleert economische ketens van-wieg-tot-graf. De precieze invulling van "de integrale keten" kan op verschillende manieren gemaakt worden. Elk vraagt om een eigen corresponderend analytisch instrument. In het kader van dit proefschrift is de *stofketen* het relevante type keten. Andere ketentypes zijn bijvoorbeeld produktketens met als corresponderend analytisch instrument de produkt-levenscyclusanalyse (LCA), en materieketens met de Materials Flux Account (MFA).

Bij het verhelderen van de rol die SFA kan spelen bij de onderbouwing van het stofgericht milieubeleid zijn niet alleen de mogelijkheden, maar ook de beperkingen van groot belang. Een eerste beperking wordt gevormd door het beperkte beeld van de economie: uitsluitend in termen van stromen en voorraden van stoffen. Met SFA kan niets gezegd worden over kosten en andere economische en maatschappelijke aspecten. Een tweede beperking is gelegen in de keuze voor één stof of stofgroep, waardoor eventuele probleemafwenteling naar andere stofketens buiten beeld blijft.

Dit proefschrift beoogt een bijdrage te leveren aan het veld van Stofstroomanalyse op twee punten: methodiekontwikkeling (deel II) en het toepasbaar maken van de methodiek voor het milieubeleid (deel III). Het onderzoek aan deze twee onderwerpen heeft tegelijkertijd plaatsgevonden: methodiekontwikkeling profiteert van bevindingen uit de praktijk; aan de andere kant is het belangrijk dat ontwikkelde methodieken inderdaad in de praktijk toepasbaar zijn. Deel IV omvat twee voorbeelduitwerkingen: cadmium en stikstofverbindingen, beide in de Europese Unie.

De SFA-methodiek (deel II)

In Hoofdstuk 2 wordt een algemeen raamwerk gepresenteerd voor materiaal- en stofstroomstudies. In dit raamwerk wordt aangegeven welke methodologische keuzes in een SFA-studie achtereenvolgens gemaakt moeten worden, hoe deze beïnvloed worden door het specifieke doel van de studie, en wat de consequenties ervan zijn voor de uitspraken die beleidmakers kunnen doen op grond van de studie. Het raamwerk bestaat uit drie elementen:

1. definitie van het te bestuderen systeem
2. kwantificering van het overzicht van stromen en voorraden
3. interpretatie van de resultaten.

De *definitie van het systeem* houdt nauw verband met de definitie van de "integrale keten" die het onderwerp van studie is. De systeemdefinitie heeft in de eerste plaats te maken met het

specificeren van vier basisvariabelen: stof, ruimte, tijd, en functies. Deze basisvariabelen bepalen het systeem in grote trekken. In Hoofdstuk 2 wordt het SFA-systeem, de integrale stofketen gedefinieerd. Een eerste keuze betreft de te bestuderen stof of stofgroep. Het systeem is voorts gedetermineerd met betrekking tot ruimte (een specifiek gebied) en tijd (gewoonlijk 1 jaar), maar omvat alle functies of toepassingen van de stof (groep). Een nadere specificatie kan worden gemaakt door het onderscheiden van subsystemen, het indelen van stromen en voorraden in categorieën, en het identificeren van in het systeem op te nemen processen. Het onderscheiden van nadere subsystemen is met name erg belangrijk voor de interpretatie van de resultaten (zie verderop). Als algemene regel worden twee subsystemen onderscheiden: het maatschappelijk subsysteem (ook wel: economie, technosfeer, anthroposfeer) en het milieu-subsysteem (milieu, ecosfeer, biosfeer). Dit maakt het bijvoorbeeld mogelijk om over "emissies" te spreken in termen van grensoverschrijdingen tussen de subsystemen. Argumenten kunnen ook gevonden worden voor het standaard onderscheiden van een derde subsysteem: het geologisch subsysteem (geosfeer, lithosfeer). Verdere onderverdelingen zijn mogelijk. Het onderscheiden van subsystemen leidt gewoonlijk tot praktische afbakeningsproblemen, die het best praktisch opgelost kunnen worden.
Bij de algemene SFA-systeemdefinitie wordt een typologie van stromen gemaakt die voor economie en milieu zoveel mogelijk in gelijke termen is gesteld. Dit sluit aan bij de analogie tussen biosfeer en technosfeer uit het concept *industrial metabolism.*
Een laatste belangrijk punt is de definitie van de economische en milieuprocessen die binnen het systeem plaatsvinden. Deze processen bepalen in feite het pad dat de stof aflegt door economie en milieu. Het aggregatieniveau waarop deze processen het best gedefinieerd kunnen worden hangt af van het ruimtelijk schaalniveau waarop de analyse plaatsvindt.
Het is van belang, dat de systeemdefinitie voor de hierboven beschreven aspecten voor elke SFA studie expliciet plaatsvindt, hoe precies hangt af van het specifieke doel van de studie.

Drie mogelijkheden worden behandeld met betrekking tot de *kwantificering van het overzicht van stromen en voorraden:*

- stofboekhouding: het achteraf registreren van de omvang van stromen en voorraden. Deze vorm van kwantificeren maakt het mogelijk trends te signaleren en de invloed van bepaalde ontwikkelingen of beleid achteraf te monitoren;
- statische modellering: het specificeren van de verbanden tussen stromen en voorraden, waardoor de herkomst van vervuilingsproblemen opgespoord kan worden en een inschatting gemaakt kan worden van de effectiviteit van bepaalde maatregelen in een evenwichtssituatie;
- dynamische modellering: het opnemen van de tijd als modelparameter, zodat voorspellingen en toekomstverkenningen kunnen worden uitgevoerd.

Er is geen "beste" keuze: elke mogelijkheid kan zinvol zijn en elk heeft eigen beleidsondersteunende potenties. Elk stelt andere eisen aan de benodigde gegevens en aan de benodigde mate van nauwkeurigheid van de uitkomsten. Dit laatste punt speelt speciaal bij de keuze tussen statische en dynamische modellering: dynamische modellering levert een toekomstvoorspelling die redelijk accuraat moet zijn om te kunnen dienen als basis voor beleid; met comparatief statische modellering kan een uitspraak gedaan worden over de zinvolheid van maatregelen in vergelijking met andere zonder een voorspelling te doen, waarmee een aantal onzekerheden wordt omzeild en een veel grotere onzekerheidsmarge acceptabel is. In Tabel S.1 worden de gebruiksmogelijkheden van de drie typen kwantificering samengevat.

Tijdens het proces van kwantificering moet een aantal keuzes gemaakt worden:

- aanwijzen van vaste variabelen: fysieke of economische causaliteit
- aanwijzen van sluitposten
- afleiden van distributiecoëfficiënten
- al dan niet opnemen van voorraad-variabelen.

Hoe deze keuzes het best kunnen worden gemaakt wordt bepaald door de specifieke SFA-toepassing, waarvan er in Hoofdstuk 5 een aantal wordt beschreven (zie verderop in het onderstaande). Soms zullen ook praktische overwegingen, bijvoorbeeld de beschikbaarheid van gegevens, een rol spelen.

Tabel S.1 Modelleringstechnieken en hun toepassingsmogelijkheden

type kwantificering / toepassing	boekhoudsysteem	statisch model	dynamisch model
signaleren problemen	+		
signaleren trends	+		
beleidsevaluatie ex post	+		
herkomstanalyse		+	
regime vergelijking		+	
beleidsevaluatie ex ante		+	+
extrapoleren trends			+
toekomstvoorspellingen			+
scenario-analyse			+

Met betrekking tot het derde element van het raamwerk, de *interpretatie van de resultaten,* zijn twee routes verkend: de beoordeling van specifieke stromen of voorraden uit het gekwantificeerd overzicht, en de definitie van indicatoren voor integraal ketenbeheer.

De mogelijkheden voor een directe evaluatie van het overzicht, zonder aanvullende gegevens en zonder extra berekeningen, zijn beperkt maar niet onbelangrijk. Een samenvatting van het overzicht kan worden geschetst met behulp van het stofstroomschema, zoals dat in verschillende hoofdstukken is gepresenteerd. Dit overzicht geeft een beeld van de verschillende in- en uitstroom-categorieën, de relatieve omvang van de economische stromen ten opzichte van die in het milieu, en de relatieve en absolute bijdrage van emissies aan de milieustromen. Een ander type samenvatting is die van de economische levenscyclus van de stof, die een beeld geeft van de omvang van de economische keten en de lekken daaruit in absolute en relatieve zin, waarmee reeds een eerste beleidsaanbeveling mogelijk wordt.

De milieustromen uit het overzicht kunnen verder worden geëvalueerd door informatie met betrekking tot hun schadelijkheid toe te voegen. Door introductie van milieukwaliteitseisen kan bezien worden of normoverschrijding plaatsvindt; emissiedoelstellingen kunnen daarbij worden gerelateerd aan stromen terwijl concentratienormen betrekking hebben op voorraden in milieucompartimenten. Een tweede mogelijkheid is het gebruik van equivalentiefactoren uit de LCA, waardoor het mogelijk wordt grote groepen stoffen in één analyse te omvatten. Een nadeel van deze benadering is het verlies aan informatie over het optreden van milieuproblemen binnen het beschouwde gebied. Een derde mogelijkheid die genoemd kan worden is de herkomstanalyse, waarmee specifieke stromen in het milieu kunnen worden teruggevolgd naar hun oorzaken.

Voor economische stromen zijn geen normen, limieten of doelstellingen geformuleerd. Desondanks zou het zeer nuttig zijn deze stromen te beoordelen vanuit het perspectief van de milieustromen die zij (zouden kunnen) veroorzaken. Een dergelijke beoordeling kan dienen als een *early warning* systeem, en daarmee tevens als een aanbeveling voor het milieubeleid. In Hoofdstuk 4 wordt voor dit doel een set indicatoren gedefinieerd, waarvan er een aantal nader wordt uitgewerkt:

Uitputting
- *primaire input:* totale instroom van primair materiaal in het economische systeem (niet nader uitgewerkt)
- *uitputting van grondstoffen:* bijdrage van het gebied aan de (mondiale) uitputting, absoluut en per hoofd van de bevolking (niet nader uitgewerkt)

Vervuiling
- *vervuilingsproblemen:* het zich voordoen van vervuilingsproblemen binnen het gebied: geselecteerde milieustromen geconfronteerd met voor het gebied geldende emissie- of concentratiedoelstellingen (uitgewerkt in § 4.3)
- *totale verliezen:* totaal aan emissies uit de economische keten (niet nader uitgewerkt)
- *ontregelingsrisico:* het risico van ontregeling van de natuurlijke stofkringloop door de economische stofkringloop of keten (uitgewerkt in § 4.4.4, economische vs. natuurlijke kringloop)
- *overschot:* vervuiling gecreëerd binnen het gebied: bijdrage van emissies in het gebied aan continentale of mondiale vervuilingsproblemen, absoluut en per hoofd van de bevolking (een voorbeeld is uitgewerkt in § 4.4.2: mineralenoverschot)

Ketenbeheer
- *efficiëntie:* de efficiëntie van de economische levenscyclus van de stof (uitgewerkt in § 4.4.3)
- *finaal gebruik:* het totale economisch gebruik van de stof als stroom of als voorraad (niet nader uitgewerkt)
- *hergebruik:* hergebruiksfractie (uitgewerkt in § 4.4.3)

Afwenteling
- *binnen het gebied:* risico voor probleemverschuiving als gevolg van maatregelen (uitgewerkt in § 4.4.3, niet-intentionaliteits-indicator)
- *naar de toekomst:* accumulatie in het milieu (§ 4.4.2) en in de economie (§ 4.4.3)
- *naar andere gebieden:* vervuiling/uitputting in het gebied versus vervuiling/uitputting veroorzaakt ten behoeve van de bevolking van het gebied (uitgewerkt in § 4.4.3 als vervuilingsexport-indicator)

Een dergelijke set, mits voldoende uitgewerkt en getest, kan worden gebruikt om de huidige situatie of de toekomstige gevolgen van een stofregime (het huidig, of een gemodificeerd regime) te evalueren. Dit levert waarschijnlijk voldoende aanknopingspunten betreffende het stofregime vanuit een "fysieke-economie" perspectief. Het moet echter in het oog gehouden worden dat dit perspectief beperkt is. Bovendien is er zelfs binnen het fysieke-economie perspectief het probleem van het onderling waarderen van de verschillende indicatoren: als er sprake is van tegenstrijdige uitkomsten, welke indicator is dan belangrijker? Uiteindelijk is dit een kwestie die niet wetenschappelijk kan worden afgehandeld. Prefereren we een schoner milieu nu ten koste van de toekomst? Is het acceptabel om onze afvalverwerking te laten plaatsvinden in het buitenland? Deze en dergelijke vragen vormen onderdeel van een subjectieve afweging. Dit probleem wordt dringend wanneer het de bedoeling is de risico's van een bepaald stofbeheer-regime in één maat of

index uit te drukken. In dit proefschrift wordt hiertoe geen poging gedaan. In de toekomst zal dit vrijwel zeker terugkomen als een belangrijk vraagstuk.

Het gebruik van SFA ten behoeve van een integraal stofketenbeheer (deel III)

De SFA-methodiek is ontwikkeld als een analytisch gereedschap. De voornaamste beleidsondersteunende functie ligt dan ook op het gebied van de *analyse* van bestaande milieuproblemen en van mogelijke maatregelen om deze op te lossen. Aanvullend kan SFA gebruikt worden bij het *ontwerp* van stofbeheerstrategieën.

De analytische SFA-toepassingen

In Hoofdstuk 5 worden vijf analytische SFA-toepassingen onderscheiden. Elk van deze toepassingen stelt eigen, specifieke eisen aan de systeemdefinitie en aan de kwantificering van het overzicht van stromen en voorraden.

1. *status quo:* de evaluatie van de huidige situatie in een gebied. Deze SFA-toepassing kan worden gezien als een vorm van monitoring: het bijhouden van de stofstromen en de veranderingen daarin in de tijd. Deze toepassing verschaft informatie over stofgerelateerde milieuproblemen die zich voordoen, en trends daarin. De effecten van ontwikkelingen en van in het verleden gevoerd beleid kunnen worden geëvalueerd. De belangrijkste aangrijpingspunten voor regulering kunnen worden geïdentificeerd.
2. *voetafdruk:* de (wereldwijde) milieugevolgen van de consumptie in een gebied. Deze toepassing geeft inzicht in de mate waarin ten behoeve van consumptie door de bevolking van het gebied elders milieuproblemen zouden kunnen ontstaan. Deze toepassing kan ook gebruikt worden bij het inschatten van probleemafwenteling naar het buitenland als gevolg van bepaald beleid.
3. *herkomst:* de economische of milieu-oorzaken van specifieke vervuilingsproblemen in een gebied. De herkomstanalyse biedt inzicht in de herkomst van milieuproblemen op drie niveaus: de directe oorzaken, de verantwoordelijke economische sectoren, en de uiteindelijke herkomst aan de grenzen van het systeem. Deze toepassing verschaft relevante informatie voor het formuleren van maatregelen of beleid om de problemen op te lossen.
4. *oplossingen:* de vergelijking van verschillende stofbeheer-regimes op hun milieugevolgen. Deze toepassing biedt inzicht in de consequenties - zowel de effectiviteit als de probleemafwenteling - van bepaalde maatregelen of veranderingen in het regime. Deze optie, gebaseerd op comparatief statisch modelleren, is geschikt voor het inschatten van richtingsveranderingen, niet voor het doen van absolute uitspraken.
5. *voorspellingen:* de voorspelling van een toekomstige situatie onder bepaalde aannames. Dit is de meest bewerkelijke SFA-toepassing, omdat gebruik gemaakt moet worden van dynamische modellering. Mits operationeel (wat nu niet het geval is) kan deze toepassing worden ingezet voor scenario-analyse en voor een evaluatie van regimes in absolute zin, i.e. voor het bepalen in hoeverre in een specifiek jaar in de toekomst beleidsdoelstellingen zullen worden gehaald onder bepaalde aannames.

Het ontwerp van stofbeheer-strategieën

De ontwikkeling van stofbeheer-strategieën is het onderwerp van Hoofdstuk 6. Het doel van dit hoofdstuk is, na te gaan in hoeverre het mogelijk is om algemene, gemakkelijk te verkrijgen informatie over een stof te gebruiken als een basis voor een beheersstrategie van die stof. Dit zou een aanzienlijke stroomlijning van het stofbeleid kunnen betekenen. In Hoofdstuk 6 worden economische stofeigenschappen geformuleerd, gebaseerd op de fysisch/chemische en andere stofeigenschappen aan de ene kant, en informatie over de toepassingen van de stof aan de andere

kant. Deze economische stofeigenschappen kunnen worden gebruikt voor het trekken van conclusies omtrent de zinvolheid van maatregeltypen in het algemeen. Economische stofeigenschappen zijn in drie categorieën ingedeeld:

functionele eigenschappen	voorraad- en materiaaleigenschappen	intentionaliteits-eigenschappen
vervangbaarheid	uitputbaarheid	intentionaliteit van winning
misbaarheid	vernieuwbaarheid	intentionaliteit van vorming
	synthetiseerbaarheid	intentionaliteit van gebruik
	concentratie	
	herwin baarheid	
	afval/emissie ratio	
	afbreekbaarheid	

Een protocol wordt gepresenteerd, waarmee een eerste grove schets van een stofbeheer gemaakt kan worden. In dit protocol wordt een lijst van tien algemene opties voor maatregelen geconfronteerd met de economische eigenschappen van de stof om een beeld te krijgen van de zinvolheid van deze opties in principe. Een strategie kan dan worden opgebouwd uit de zinvol gebleken opties. De opties zijn:

1. preventie van winning of vorming
2. extractie van de sporeverontreiniging uit het gastheermateriaal
3. technisch sluiten van proceslekken (inclusief het opvoeren van de efficiëntie)
4. beëindigen van gebruik of toepassing (inclusief substitutie door andere stoffen)
5. hergebruik a: inzamelen en produkthergebruik (afhankelijk van produkteigenschappen)
6. hergebruik b: inzamelen, extractie en hergebruik van de stof
7. hergebruik c: hergebruik van afvalmaterialen (compost, vliegas, dierlijke mest enz.)
8. afvalverwerking a: inzamelen en stort
9. afvalverwerking b: inzamelen en afbraak (mogelijk, maar niet per se door verbranden)
10. afvalverwerking c: inzamelen en immobilisatie.

De algemene beheersstrategie-aanduidingen voor cadmium en stikstof zoals gepresenteerd in Hoofdstuk 6 zijn schetsmatig. Aan de andere kant zijn ze wel alomvattend, en ze lijken de verschillende, meer of minder vanzelfsprekende, vormen van probleemafwenteling te vermijden. Op dat algemene niveau deugen ze, en kunnen daarom dienen als basis voor een nader in te vullen beleid. Het lijkt erop dat het mogelijk is een verbinding te leggen tussen algemene, gemakkelijk te verkrijgen stofgegevens en de hoofdlijn van een beheersstrategie voor de stof. Het is denkbaar, grotere groepen stoffen met gelijke economische eigenschappen onder één strategie te brengen. Het idee van economische stofeigenschappen is echter nog onvoldoende ver ontwikkeld om nu al algemeen toepasbaar te zijn. Bovendien zal voor een meer gedetailleerde invulling van een beheersstrategie meer informatie nodig zijn. Dit hoeft zeker niet in alle gevallen een complete SFA-studie te zijn. Een SFA-studie wordt wel aanbevolen voor stoffen met een gecompliceerde economische keten of kringloop, en voor stoffen die gedurende langere tijd in het economisch systeem verblijven.

De voorbeelduitwerkingen (deel IV)

Zoals hierboven reeds aangegeven, zijn twee voorbeelduitwerkingen gemaakt: cadmium en stikstofverbindingen in de Europese Unie. Deze zijn gepresenteerd in de hoofdstukken 7 en 8. Deze case studies hebben primair een rol vervuld bij de methodiek-ontwikkeling, maar leveren ook zelfstandige conclusies op. De belangrijkste SFA-toepassingen waren in beide gevallen de

status quo, de *herkomst*, en de *oplossingen* toepassingen. De resultaten van deze SFA-toepassingen zijn gebruikt voor het becommentariëren van reeds vast- en voorgesteld beleid, en het schetsen van aanvullende of alternatieve mogelijkheden voor een oplossing van de aan de stof gerelateerde milieuproblemen.

Cadmium

De produktie en het gebruik van cadmium in de EU heeft geleid tot milieuproblemen. De volgende probleemstromen zijn, in volgorde van beheersbaarheid, uit de SFA-studie naar voren gekomen:

- **de belasting van de landbouwgronden**
- **de belasting van het oppervlaktewater**
- vuilstortlokaties
- **economische accumulatie.**

Als directe oorzaken voor deze probleemstromen zijn allerlei verschillende stromen aan te wijzen. Op het niveau van de sectoren kan geconcludeerd worden, dat in alle gevallen dezelfde sectoren bijdragen, maar in zeer verschillende mate. Uiteindelijk kunnen alle probleemstromen worden teruggevoerd naar twee hoofd-instromen: import van fosfaaterts, en import en winning van zinkerts. Zinkerts is de voornaamste bron van de intentionele cadmium-toepassingen, die voor het grootste deel eindigen op de vuilstort of accumuleren in het economisch systeem. In fosfaaterts komt cadmium voor als een verontreiniging, waardoor ook het voornaamste produkt, fosfaatkunstmest, cadmium bevat en cadmium zodoende opgenomen wordt in de agrarische materiekringloop.

In het geval van cadmium zullen de gangbare begrippen van bestrijding-bij-de-bron enigszins geamendeerd moeten worden. Het EG-beleid, dat is geformuleerd volgens (1) *end-of-the-pipe* maatregelen, (2) beëindigen van een aantal cadmium-toepassingen, en (3) recycling van cadmiumbevattende batterijen en cadmeren, zal leiden tot verschillende vormen van probleemafwenteling:

- diffuse emissies worden vervangen door lokale emissies
- emissies binnen de EU worden vervangen door emissies daarbuiten
- emissies nu worden vervangen door emissies later.

Dit beleid zal uiteindelijk niet tot de gewenste resultaten leiden, hetgeen vooral wordt veroorzaakt door het buiten beschouwing laten van het inelastisch cadmium-aanbod, dat wil zeggen, voor het grootste deel als bijprodukt van zink.

Voor een effectief beleid is het vereist in te spelen op de wijze van intrede van cadmium in het economisch systeem. Aan de instroom-kant zullen maatregelen moeten worden geformuleerd die gericht zijn op zink en fosfaat, en niet op cadmium zelf. Als dat niet gebeurt, zullen cadmium-gerichte maatregelen zoals hergebruik van batterijen alleen leiden tot een verhoogde beschikbaarheid van cadmium, en daarmee tot grotere toekomstige emissies. Aan de uitstroom-kant lijkt inzameling en vervolgens veilig opbergen van cadmium bevattende produkten en afval de beste mogelijkheden te bieden, mede uit oogpunt van uitputting van grondstoffen. Tot op zekere hoogte kunnen deze conclusies gegeneraliseerd worden. Alle ertscontaminanten, die geheel of voor een belangrijk deel worden gewonnen als bijprodukt van andere grondstoffen, zullen min of meer ditzelfde gedrag vertonen. Het in de beschouwing betrekken van dergelijke karakteristieken van vraag en aanbod is onmisbaar bij het formuleren van een succesvol stofbeleid.

Stikstofverbindingen

Er zijn verschillende milieuproblemen gerelateerd aan stikstofverbindingen, die zich op verschillende schaalniveaus voordoen. In Hoofdstuk 8 zijn deze problemen in samenhang geanalyseerd door de EU te beschrijven als een systeem van onderling samenhangende

stikstofstromen. Van drie specifieke stikstofproblemen is de herkomst getraceerd: de atmosferische depositie van NO_x en NH_3 op natuurgebieden, de uitspoeling van nitraten naar het grondwater, en de anthropogene belasting van de Noordzee met stikstofverbindingen. De directe oorzaken zijn sterk verschillend voor de verschillende problemen, maar de belangrijkste uiteindelijke herkomst blijkt voor alle drie de produktie van stikstofkunstmest uit atmosferisch stikstofgas te zijn, en de voedselproducerende en -consumerende sectoren de belangrijkste doelgroepen. Hoewel de problemen zich voordoen op verschillende schaalniveaus, wordt de belangrijkste oorzaak gereguleerd op EG-niveau: het EG landbouwbeleid.

Maatregelen en beleid ter bestrijding van stikstofgerelateerde milieuproblemen zijn geformuleerd door verschillende lidstaten maar ook door verschillende internationale organisaties. De belangrijkste zijn verwoord in de EG Nitraatrichtlijn en in de INSC en ParCom voorstellen voor de bescherming van de Noordzee. De wijzigingen in het EG landbouwbeleid als gevolg van het Plan-MacSharry lijken de stikstofstromen nauwelijks te beïnvloeden. De milieuproblemen zijn zodoende niet zozeer aan de overproduktie, maar aan de reguliere zelfvoorzienende landbouwproduktie te relateren.
De meeste maatregelen die voorgesteld worden in de verschillende akkoorden en beleidsstukken hebben een technisch, *end-of-the-pipe*karakter. Bij een succesvolle implementatie hiervan lijken twee van de drie problemen aanzienlijk te verminderen, zij het niet tot het gewenste niveau. De derde probleemstroom, de uitspoeling van nitraten naar het grondwater, neemt in het geheel niet af. Dit heeft te maken met het feit dat de belangrijkste oorzaak, de stikstofstroom in de landbouw die uiteindelijk afkomstig is uit stikstofkunstmest, nauwelijks wordt beïnvloed.

Om alle drie problemen op te lossen zijn andere maatregelen nodig, en ook denkbaar. Een aantal is doorgerekend op hun effecten.
Het beëindigen van de import van landbouwprodukten (m.n. veevoer) van buiten de EG heeft slechts een beperkte invloed op de drie probleemstromen. Afhankelijk van de precieze aannames kunnen kleine veranderingen ten goede of ten slechte verwacht worden.
Een extreem programma van technische maatregelen, onder andere omvattend een 90% emissiereductie van alle emissies naar lucht, behandeling van alle huishoudelijk en industrieel afvalwater met denitrificatie, centrale mestverwerking voor 25% van alle dierlijke mest, en efficiëntieverhogende maatregelen in de landbouwbedrijfspraktijk, zou twee van de drie probleemstromen volledig kunnen oplossen. De uitspoeling van nitraten naar grondwater zou echter grotendeels onopgelost blijven. Het lijkt erop dat oplossing van het nitraat-naar-grondwater probleem niet in overeenstemming is te brengen met de EU-landbouw volgens de huidige opzet en doelstellingen, maar drastische maatregelen zou vereisen. Twee mogelijke richtingen zijn verkend, door het inschatten van de effecten van de meest extreme invulling ervan: (1) een drastische verlaging van de stikstofinput door een terugkeer naar het pre-kunstmest tijdperk, modeltechnisch door produktie en gebruik van kunstmest op nul te stellen, en (2) een drastische verhoging van de efficiëntie van de landbouw via een overstap op een voedselproduktie en -consumptie zonder dierlijke produkten, modeltechnisch door de veehouderij als procesgroep te elimineren. Beide opties lijken effectief te zijn: de eerste door het reduceren van de stikstofkringloop in de landbouw tot een tiende van de huidige omvang, en de tweede door het verdrievoudigen van de efficiëntie van de landbouw. Hoewel effectief, zouden dergelijke extreme scenario's enorme implicaties voor de maatschappij hebben. In het eerste geval zou, doordat ook de output van de landbouw sterk gereduceerd wordt, de EU-bevolking in hoofdzaak van geïmporteerd voedsel moeten leven, hetgeen in feite een export van milieuproblemen zou betekenen. In het tweede geval betekent de aanname in feite dat de gehele EU-bevolking zou overstappen op een compleet veganistisch dieet. In beide gevallen zouden grote delen van de landbouw verdwijnen. Een compromis-scenario, waarmee de nitraatbelasting van het grondwater grofweg zou worden gehalveerd, zou minder extreme maar toch nog steeds grote veranderingen met zich meebrengen.

Het formuleren van een oplossing voor deze problemen in de EU betekent het doorhakken van een geweldige economie-milieu knoop. Aan de ene kant vervullen stikstofverbindingen (eiwitten) een niet vervangbare basisfunctie als voedingsstoffen. Aan de andere kant zijn de milieuproblemen die gerelateerd zijn aan de agrarische stikstofcyclus groot. Het oplossen van deze problemen vereist radicale en mogelijk zelfs ontwrichtende veranderingen. De uiteindelijke *bottom line* is een maatschappelijke keuze: kiezen we ervoor de milieuproblemen op te lossen tot op het in richtlijnen en overeenkomsten vastgestelde niveau, of kiezen we ervoor de voedselproduktie en -consumptie min of meer de huidige aard en omvang te laten behouden? Op dit moment zou een voorstel voor het afzwakken van de nitraat-norm van 50 mg/1 zeker te verdedigen zijn. In de toekomst zou echter een steeds groeiende EU- en wereldpopulatie ons kunnen dwingen tot een heroverweging van de radicale veranderingen in voedselproduktie en -consumptie zoals bovengeschetst. Wanneer ook dan nog geldt, dat technische maatregelen de problemen onvoldoende kunnen oplossen, zullen dergelijke drastische opties misschien de enige zijn die de toekomstige milieuproblemen kunnen oplossen.

Algemene discussie, conclusies en aanbevelingen

In hoofdstuk 10 wordt teruggeblikt op de voorgaande hoofdstukken vanuit een breder perspectief. Dit heeft betrekking op

- de positie van SFA in het veld van integrale ketenanalyse
- de verdere wetenschappelijke ontwikkeling van SFA
- de potenties van SFA als gereedschap ter ondersteuning van het milieubeleid.

De plaats van SFA in het veld van integrale ketenanalyse

SFA is ontwikkeld als een analytisch gereedschap ter ondersteuning van een integraal stofketenbeheer. Als zodanig heeft het mogelijkheden, maar ook beperkingen. Een duidelijk beeld van de laatste is van groot belang.

In de eerste plaats dienen geen uitspraken gebaseerd te worden op een SFA-studie die buiten het kader van een integraal stofketenbeheer vallen. De twee principiële beperkingen die daarmee samenhangen zijn:

1. Vanuit het SFA-perspectief bestaat de wereld uit stromen en voorraden van stoffen. Elke uitspraak dient zich tot dat perspectief te beperken.
2. Een SFA-studie is beperkt tot één stof of een beperkte groep stoffen per keer. Afwenteling van problemen naar andere stofketens kan hooguit in kwalitatieve termen gesignaleerd worden. Ander analytisch gereedschap, zoals LCA of MFA, is geschikter voor het bestuderen van dergelijke afwentelingsmechanismen.

In de tweede plaats is er de vraag naar standaardisatie van het SFA-instrument. Tot nu toe is weinig aandacht besteed aan harmonisatie van de verschillende activiteiten in het veld. Om enige vorm van harmonisatie te bereiken, moet op twee gebieden de discussie aangezwengeld worden:

1. De relatie van SFA tot de andere analytische instrumenten in hetzelfde veld. Er is reeds opgemerkt dat deze instrumenten veel gemeenschappelijk hebben. De ontwikkeling van de verschillende methodieken zou er baat bij hebben wanneer dit in overleg zou gebeuren, niet alleen via het helder krijgen van de verschillen, maar ook door het adopteren van gelijke procedures op punten waarop de methodieken wel gelijk zijn.
2. Het SFA-gereedschap zelf. Het algemene raamwerk zoals dat gedefinieerd is in Hoofdstuk 2 kan gebruikt worden voor elke SFA-toepassing. Het zou een belangrijke stap voorwaarts betekenen als er consensus kon worden bereikt over een dergelijk algemeen raamwerk, over de keuzes die daarbinnen gemaakt moeten worden, en over een procedure om deze keuzes in concreto te maken afhankelijk van de specifieke SFA-toepassing.

Aanbevelingen voor een verdere ontwikkeling van SFA

De belangrijkste discussie ten aanzien van de systeemdefinitie is die omtrent de afhankelijkheid daarvan van de specifieke vragen waarop een SFA-studie antwoord moet geven. Er zou al veel verhelderd worden door het goed scheiden van de "functionele" en de "regionale" invalshoeken.

Er zijn diverse belangrijke discussies met betrekking tot het kwantificeren van het overzicht van **stromen en voorraden:**

- beschikbaarheid en kwaliteit van gegevens: voor SFA-studies op het niveau van EG-lidstaten moet een oplossing gevonden worden voor de recente degradatie van de handelsstatistieken, waarin sinds 1992 uitsluitend monetaire gegevens gepresenteerd worden. Een tweede probleem is het ontbreken van gegevens over economische en milieu-voorraden. Een inventarisatie hiervan wordt sterk aanbevolen, als een voorwaarde voor een succesvolle *voorspellingen*-toepassing van SFA.
- modelleren: aandacht voor het ontwikkelen en implementeren van dynamische stofstroom-modellering wordt aanbevolen, hoewel het overheersend belang hiervan in dit proefschrift iets wordt gerelativeerd. Een ander aspect is de inbreng van meer economische causaliteit in de modellering. Tot nu toe is de economische causaliteit beperkt tot de beslissing het model vraaggestuurd of aanbodgestuurd op te zetten. Zeker voor de *oplossingen* en *voorspellingen* toepassingen zou een grotere inbreng van economische mechanismen wenselijk zijn.
- voor een evaluatie van de kwantificering-stap wordt de ontwikkeling van een standaard gevoeligheidsanalyse procedure, die voor elke case studie kan worden toegepast, ten sterkste aanbevolen.

Voor de interpretatie van de resultaten wordt nadere aandacht aanbevolen voor het koppelen van de SFA-resultaten aan bestaande evaluatiesystemen, zoals bijvoorbeeld risico-analyse modellen of een evaluatieprocedure zoals bij de LCA gehanteerd wordt. Op die manier sluiten de resultaten beter aan bij voor beleidmakers bekende begrippen. Een volgende aanbeveling is het verder uitwerken van een set van indicatoren, waarmee kan worden gemeten in hoeverre de doelen van integraal stofketenbeheer worden bereikt.

Een andere ontwikkelingslijn is gelegen in het koppelen van stofstroommodellen aan andere modellen. Alvorens zo'n koppeling te realiseren is wel zorgvuldig nadenken vereist over of, en zo ja hoe dit kan worden gerealiseerd. Aan de input-kant kan bijvoorbeeld gedacht worden aan een relatie met economische scenario-modellen, waarvan de output een input voor een SFA-model kan vormen. Aan de output-kant kan men denken aan een verbinding met *fate* modellen voor het milieu, bijvoorbeeld met een algemeen multimedia-model of met een ruimtelijk gedifferentieerd milieumodel. Tenslotte zou een koppeling met een economisch evaluatiemodel gewenst zijn, om de evaluatie van fysieke veranderingen te kunnen koppelen aan die van economische veranderingen. Het toevoegen van deze dimensie zou ook mogelijkheden openleggen voor het optimaliseren van maatregelpakketten naar de kosten ervan.

De potenties van SFA voor het milieubeleid

In de voorbeelduitwerkingen, cadmium en stikstofverbindingen, heeft SFA met name een rol gespeeld bij het leggen van een kwantitatief verband tussen economie en milieu. Dit heeft tot enkele nieuwe inzichten geleid met betrekking tot de samenhang van ogenschijnlijk verschillende milieuproblemen, en de zinvolheid van bepaalde maatregelen. De belangrijkste bijdrage ligt echter op het niveau van het systeem als geheel, door het inzichtelijk maken van de verschillende vormen van probleemafwenteling die hand in hand gaan met de verschillende typen oplossingen.

Op dit moment kunnen de volgende SFA-toepassingen aanbevolen worden voor gebruik ten

behoeve van het milieubeleid:

- de reeds in de praktijk gebruikte *status quo* toepassing voor het volgen van de ontwikkeling van stofstromen en -voorraden in de tijd
- de *herkomst* en de *oplossingen* toepassingen voor het identificeren en toetsen van verschillende opties voor een deugdelijke beheersstrategie voor stoffen.

Voor de *voetafdruk* en de *voorspellingen* toepassing geldt, dat verdere ontwikkeling vereist is alvorens zij min of meer standaard kunnen worden gebruikt. Het is in het belang van het milieubeleid dat beleidmakers deze verdere ontwikkeling van het SFA-instrument bevorderen. Wellicht is dit voor hen de enige mogelijkheid om de richting van deze ontwikkeling daadwerkelijk te beïnvloeden, en daarmee ook de gebruiksmogelijkheden van het SFA-gereedschap voor hun doeleinden.

Tenslotte wordt in Hoofdstuk 10 ingegaan op de noodzaak voor een vereenvoudiging van het SFA-instrument. Het uitvoeren van uitgebreide SFA-studies voor alle relevante stoffen is mogelijk noch wenselijk. Dit geldt overigens evenzeer voor andere analytische instrumenten in het veld van integraal ketenbeheer: het zal evenmin mogelijk zijn LCA-studies voor alle relevante produkten uit te voeren, of risico-analyses voor alle relevante situaties. Het is daarom belangrijk dat zowel de wetenschappers als de beleidmakers die zich bezig houden met het ontwerpen van deze instrumenten ook aandacht besteden aan het stroomlijnen ervan. Dit kan op verschillende manieren gestalte krijgen:

- het ontwerpen van vereenvoudigde versies van de analyse-instrumenten
- het definiëren van algemene vuistregels op basis van de patronen die uit de toepassing van de instrumenten naar voren komen
- het onderscheiden van grotere groepen stoffen om in één analyse te omvatten
- expliciet maken, in welke gevallen er een echte noodzaak is voor toepassing van de analyse-instrumenten, en in welke gevallen het milieubeleid ook zonder kan.

PART I INTRODUCTION

Part I, containing only one chapter, serves as a general introduction to this thesis. A description is given of the field of Substance Flow Analysis and the aims of this thesis are defined in terms of a contribution to this field.

SFA is described as an analytic tool in the scientific field of industrial ecology, as one possible operationalization of the concept of industrial metabolism. This concept draws an analogy between the processes of mobilization, use and excretion of materials by living organisms in the biosphere, and the processes in the economy or technosphere. With this view of the economic system, strictly in physical terms, it becomes possible to quantify the economy-environment relationship.

The environmental policy area that is closely linked to industrial ecology is the area of integrated chain management, in which resource management and pollution policy are combined. The basic idea is to make economic material chains "from cradle to grave" the subject of policies. The integrated chain can be defined in various ways. SFA is related to the substance chain, and therefore to substance policy.

This thesis aims to contribute to the field of SFA in two directions: (1) the development of SFA methodology, and (2) the specification of the role of SFA in environmental policy.

CHAPTER 1 INTRODUCTION

1.1 Aims and scope, definition of substance flow analysis

The economic production, use and disposal of materials is a cause of major environmental problems. In circles of both economists and environmentalists, resource depletion is identified as a major problem. Still more pressing are the pollution problems arising from the emission of hazardous substances into the environment. These emissions occur to such a degree that the environment is threatened on a global scale. One can examine pollution problems and their origins from many different viewpoints, and come up with widely varying types of solutions, but in the end, these solutions must all be based on an analysis of the problem in physical terms: the flows of the substances themselves. Substance Flow Analysis (SFA), to which this thesis intends to contribute, is an analytical tool that has been developed to support environmental policy with regard to the societal or economic management of substances. In general terms, the aim of SFA can be defined as: the establishment of a quantified relationship between the economy and the environment of a geographically demarcated system by the quantification of the pathways of a substance or group of substances in, out and through that system. This physical perception of the economy categorizes SFA as one possible operationalization of the concept of *industrial metabolism.* It can also be viewed as an analytical instrument in the field of *integrated chain management.*

This thesis aims at (1) contributing to SFA methodology by developing a general framework for conducting SFA studies, and specifying the separate steps of this framework, and (2) specifying the potential role of SFA for supporting environmental policy. In Section 1.2, a description is offered of the position of SFA in the field of environmental science and policy. Some basic concepts, specifically the economy-environment relationship, the concept of industrial metabolism, and the integrated chain management, are discussed. The relation to other analytical tools in this field is briefly discussed as well.

In several places, SFA studies and other studies with comparable goals and set-ups have been conducted. Existing applications differ in their modelling techniques, their system's definition, the comprehensiveness of the analysis, the level of detail, and the level of aggregation, among others factors. For all, however, the *materials balance* approach has been an important starting point, providing a common basis for all these approaches. Nonetheless, so far there has been very little attention directed to the harmonization of these efforts. Section 1.3 is dedicated to a short historic overview of SFA development, also related to SFA-type studies conducted at other institutes.

Methodology development benefits from testing the theories in practical applications. On the other hand it is important that developed methodologies can be used in practical applications. Almost from the start of the thesis research, therefore, attention has been directed toward case studies and simultaneous translation of the various methodological steps in a computer program. In Section 1.4 the case studies are briefly introduced.

Finally, Section 1.5 contains a short description of the contents of this thesis.

1.2 The scientific field

The economy-environment relationship

Environmental policy is concerned with the environmental problems arising from human economic

activities, and the abatement of those problems. The central issue in this field, therefore, has been identified as the economy-environment relationship. This issue can be approached from many directions, each approach giving additional insights and leading to its own set of relevant conclusions. Costanza and others (Costanza, 1991) have defined a new branch of science, which has the economy-environment relationship as its prime object and which tries to integrate economic and ecological questions by an interdisciplinary approach: ecological economics. Important questions in scientific discussions on this subject are, among others, whether there should and can be a 'valuation' of environmental resources, possibly in monetary terms, thereby including the environment as a production factor ("natural capital") and so making it possible to incorporate environmental parameters in economic plans and decisions (Costanza, 1991; Daly, 1980). Another possibility is to find a common measure for the economy and the environment in physical terms, such as (embodied) energy (Odum, 1983). Yet another approach to the economy-environment relationship is made from a functional angle, connecting environmental parameters to specific economic functions. An instruments for doing so is, for example, Natural Resource Accounting (NRA) — although this concept is not clearly defined and is used in different ways, it boils down to specifying, in very general terms, the goods and services the environment delivers to the society (Odum, 1989; Barbier, 1989).

Industrial metabolism and industrial ecology

Another basic concept that has been developed to enlighten the economy-environment relationship is that of *industrial metabolism,* as defined by Ayres (1989). This concept argues the analogy between the economy and environment on a material level: the economy's "metabolism" in terms of materials mobilization, use and excretion to create "technomass" is compared to the use of materials in the biosphere to create biomass. Whereas the biosphere has had billions of years to evolve and attune its processes to such a state that waste generated in one process is converted into a resource for another, the economy is still in its early stages of wastefulness. In order to speed up 'economic evolution', society must look to the biosphere for guiding principles. The description of the economy thus is limited to a description of the *physical economy.* The research area of *industrial ecology* (Jelinski et al., 1992) occupies itself with elaborating and operationalizing this concept, and takes the physical economy as its primary subject. An important research instrument in this field is the *materials balance,* a tool for describing the materials regime of the economy based on the Law of Mass Preservation, again analogous to the long-standing practice of investigating ecological materials cycles (Kormondy, 1976). Substance Flow Analysis is based on the materials balance approach. It can be said to offer the economic counterpart to the study of ecological materials flows, thus extending the concept of biogeochemical cycles and opening possibilities to study their transformation into *anthropo-*biogeochemical cycles.

Integrated chain management and analysis

The environmental policy area that is closely linked to industrial ecology is the area of integrated chain management, in which resource management and pollution policy are combined. The basic idea is to make economic material chains *from cradle to grave* the subject of policies. Thus, pollution can be traced to its causes and finally linked to the use of resources, and the question of responsibility for environmental problems can be addressed more adequately. Moreover, when contemplating abatement strategies, focusing on the integrated chain offers openings to spot various mechanisms of problem shifting. It has been, and still is, one of the aims of environmental science to develop instruments for *integrated chain analysis* to support this type of policy.

The "integrated chain" can be defined in various ways, be it always "from cradle to grave". Each definition has its own policy area and its own need for corresponding analytical tools. A few possibilities are mentioned here:

1. *mass total chains.* Following mass chains and drawing up mass balances is in fact one of the oldest ways of quantifying the physical economy. Most of the time, the investigation of total mass chains is linked to the level of national or regional economies and the analytical tool employed for the investigation is the materials flow account (MFA) (Bringezu, 1993), which can be used to comment on a society's overall materials intensity. In this area, discussions regarding the link between GNP and total materials consumption are important, as well as their possible de-linking in the developed countries (Jänicke et al., 1989; Stern et al., 1994; De Bruyn & Opschoor, 1994). Mass chains can also be defined according to a functional demarcation, for which Schmidt-Bleek (1993) defined the concept of MIPS (Materials Intensity Per unit of Service).

2. *product chains.* In a product chain, a specific product or service is the starting point. The required raw materials and energy (the cradle), industrial and trade processes, and concurrent emissions of this product are specified. "Downchain", the discarding and waste treatment associated with the product are specified (the grave). The analytical instrument for specifying such chains is the product life cycle assessment (LCA) (Guinée, 1995), which was developed to compare different alternatives for providing the same function, and therefore can be used to support a products policy. This approach can also be used for functions at a higher level, for example a society's food provision, energy supply, or transport system. Opschoor (1994) defines the *materials-product-chain,* starting from the life-cycle of a product, but regarding the flows of one specific substance or material through that chain. Such a strictly limited definition of a chain opens possibilities to evaluation of both economic and environmental aspects.

3. *materials chains.* A specific material or group of materials, such as paper, fossil fuels, or plastics, is the central object in this type of chain. Production, use and disposal of the material are studied. This approach is often taken to establish possibilities for reuse and recycling on behalf of waste management policies. An example is the study regarding fly-ash by Olsthoorn et al. (1991). For this type of chain, major difficulties are often encountered regarding its definition, since neither the function (as in product chains) nor the composition (as in substance chains) of such materials offers a solid basis for definition.

4. *substance chains.* In the case of a substance chain, the life cycle of one substance or group of substances (either elements or compounds) is followed, from the extraction of it in raw materials or its primary production from basic chemicals, through its economic applications, to its ultimate environmental fate. The concurrent analytical tool is substance flow analysis (SFA), the subject of this thesis. It is linked to pollution policy, and, to a lesser degree, to resource conservation policy.

All these approaches can be useful, and all have their own policy-supporting possibilities and limitations. The corresponding analytical tools must be defined differently, although all are concerned with the analysis of materials chains. Aspects of time and location vary according to the tool used. MFA and SFA are defined in space and time, while LCA is not. The same variation can be found regarding the choice of substances and materials to be analyzed, and the level of detail required: MFA and LCA encompass all substances, SFA is limited to the one substance; LCA considers the emissions in great detail while MFA only addresses the total level. LCA and MFA are confined to the economic flows with an emission evaluation, while SFA is also occupied with the consequent environmental flows. In practice, there sometimes is confusion with regard to these different tools, and demands are made of one analytical tool that could be met more adequately by another (Van der Voet & Heijungs, 1994). This is probably caused by the fact that despite the differences, there are also many similarities. All are described as ecobalances (for example by Hofmeister (1989) and by Grieshammer et al. (1991)). Locational aspects which naturally are part of an SFA or MFA, since these are linked to regions, are required from LCA as well. A comparison of alternatives, for which LCA is suited, is also demanded from SFA/MFA.

In conclusion, we could say that the field of integrated chain analysis is in the middle of its development. Scientific discussions may be expected to bring some clarity to the field in the coming the years.

In view of the subject of this thesis, particular attention is given to the subject of substance chains, to the corresponding substance policy, and to the role of SFA in this field.
Substance-related policy has been evolving from a definition of acceptable concentrations in environmental compartments 25 years ago, through agreements on emission level targets, into an integrated substance chain management policy with appropriate attention for the societal origins of the existing problems, combining resource issues with pollution abatement, and aiming in general at "closing the cycle". This process of evolution is still in progress. An integrated substance chain management requires knowledge of two elements: the current problems and their causes; and the possible solutions and their effects. For both, SFA can play a role.

The first requirement for a substance policy is knowledge of the environmental problems related to the substance: what are the harmful effects and to what extent do they occur within the area? Often this knowledge is available. For many substance, a second step is taken as well: using this knowledge to establish acceptable environmental concentrations. The third step is to relate these concentrations to acceptable emissions. This step is more difficult and often it has not been taken adequately. We find translations from environmental concentrations into concentrations in effluents and waste streams (such as sewage sludge, manure, incineration residues), but they leave the absolute amount of the emissions, which is also important, unaccounted for.
The fourth step is relating the emissions to their physical causes in society. For this, knowledge is required of the societal life cycle of the substance, and therefore of economic processes of recovery, manufacturing, use and disposal, and of the losses into the environment during this life cycle. Knowledge regarding economic substance flows generally is available, but very fragmented and scattered. SFA can make an important contribution here by organizing this knowledge and translating it into a form that is relevant for environmental policy. What exactly this "relevant form" is depends on the specific goals of the analysis. For a substance policy, it is important to obtain a picture of the integrated chain, as well as the specific flows that are responsible for the environmental problems. A fifth step, finally, is to explain the physical substance flows in society by economic theories and other factors related to human behaviour. With that, the translation from environmental problems to their societal origins is complete. This last step is by far the most difficult and is not, to date, operational, although some steps have been taken in this direction (Wieringa & Van den Nieuwenhuijzen, 1994).

Before presenting certain policy measures as a solution for the environmental problems, there must be some idea of their effectiveness. In the first place, the effects on the signalled problem are important: will it be solved, and how long will that take? A second question refers to the possible problem-shifting mechanisms. This problem-shifting may occur within the substance chain, when one emission is replaced by another. For signalling this type of problem-shifting, SFA is eminently suited. Other forms of problem-shifting are shifting in time (from now to the future) and in space (from one region to another). This, too, can be made apparent by SFA. Shifts to other substance chains, for example by replacing one material by another, cannot be an outcome of an SFA study. For this type of problem-shifting, product LCA is more suitable. The VNCI, the Dutch branch organization for the chemical industry (Anonymous, 1991) has outlined an approach for a substance chain analysis which consists of two parts: an SFA for analyzing the problems related to the substance and marking priorities for policy, followed by a number of LCAs to compare the alternatives with the original and with each other.
When considering certain policy measures, there will also be effects that occur in quite different places, for example through the costs of the measures that will result in shifts in expenditures and

investments. Again, this is by far the most complicated step and is, in practice, limited to specifying the direct costs, if it is made at all.

13 Historic background

Neither the study of substance flows, nor the materials balance approach is a recent approach. Substance flows in ecological systems have been investigated for a long time. In the early 1980's, a boom could be detected in the study of the grand cycles (C, N, P, S) on a global level (Schlesinger, 1991), which is based on the materials balance approach, and which also includes - be it on a very general level - the human contribution. Westbroek (1992), among others, recommends a closer study of such cycles in order to reach a better understanding of the transformation mechanisms of the Earth's biosphere, and of the role of living organisms in it. The study of substance flows in the society can be viewed as an extension of this, specifying the contribution of the human economy to the global materials regime. Conducting materials flow studies as an effort to bridge the gap between economy and environment was first recommended around 1970. Victor (1972) describes and comments on some of these approaches, which mostly start from the economic Input-Output Analysis (IOA) as defined by Leontief (1966). In Input-Output tables, the mutual deliveries of goods between economic production sectors are specified on a mass basis as well as in monetary terms. A rather rigidly determined model structure has been added to that, with which the impacts of regime changes on the deliveries can be calculated. Kneese et al. (1972) make a first attempt to describe and quantify mass flows in US society. Ayres (1978) writes extensively on the subject of investigating materials' pathways through the economic system, and includes several case studies. Both MFA and SFA can be described as branches originating from this stem.

Quite apart from that, the Dutch and German Central Statistics Bureaus, and possibly of other countries as well, have been occupied with drawing balances for specific chemicals. This may have originated from the tradition within statistics of maintaining detailed bookkeeping of flows and stocks of agricultural products. The first phosphate balance for the Netherlands is for the year 1970 (Olsthoorn, 1985). In agricultural research, the balance approach has been quite common for a long time (Harenz et al., 1992; Central Bureau of Statistics, 1992). Environmental science groups became interested in this type of research in the 1970s and 1980s as well. The balance studies conducted at the Free University of Amsterdam (Teunissen et al., 1976; Feenstra and Anzion, 1980; Van Vliet and Feenstra, 1982) are early examples. At the Centre of Environmental Science of Leiden University, the first encounter with the materials balance approach occurred in 1986, when a student group designed a way to account for the economic pathways of specific substances as an information tool for environmental policy (Guinée et al., 1987; Udo de Haes et al., 1988). This Student group has laid the first foundations for the work on this thesis.

In more recent years, the idea of investigating substance flows in the economy has become more popular. Materials balance studies have been conducted from several angles. River basin studies (Stigliani & Anderberg, 1992) have shown that the origins of water pollution have been shifting from industrial pollution to consumer emissions over the past few decades. Industry-oriented studies (Ayres et al., 1989) have raised suspicions of hidden pollution problems by signalling 'missing' amounts of materials. Another fruitful application of the materials balance approach has been to investigate the flows and stocks of individual substances or substance groups in the economy of a given region (or "anthroposphere", as the authors, Brunner & Baccini (1992), call it). This application also allows the key flows or stocks for regulation in that region to be identified, and the effectiveness of certain abatement measures to be assessed. The ensuing picture of the economic life cycle of a substance may be regarded as important information for developing

a pollution policy on a regional level. Bergbäck et al. (1992) have investigated flows of metals in Sweden from a historic angle. These authors have been the first to stress the importance of accumulated stocks for present and future pollution. Also, the interest in using a substance or materials flow overview as a basis for policy instruments has been growing of late. Huppes (1993) developed the Substance Deposit as an indirect emission tax, which is based on a substance bookkeeping system on the level of a country or a group of countries. At the level of individual farms, the mineral bookkeeping system has been designed, primarily as an information system for farmers. Recently, the idea of linking this bookkeeping system to a mineral surplus tax has been introduced (Bernts et al., 1993). Also mentioned is the idea of extending the System of National Accounts with information on the state of the environment. Substance, or natural resource, accounts could be a part of that information (Huele et al., 1993).

Most studies on the materials flows conducted to date can be described as inventories: collecting as many data as possible on flows and stocks, and organizing these in an overview that can be used to draw conclusions relevant for a materials management policy. Various attempts have been made to model substance flows, as a means of predicting the changes in materials flows resulting from given societal developments or policy measures. Most of these models are concerned with relatively small parts or subchains (Gilbert & Feenstra, 1992), or focus on emissions and the environment (Alcamo et al., 1990). The use of the Input-Output Analysis technique is recently recognized more widely as a potentially useful technique for analyzing economic or societal materials flows in one model. Several practical exercises lately have been undertaken in this direction (Duchin (1994), Idenburg (1993), Konijn (1993)).

There is as yet no standardized methodology for conducting such studies. It could be argued that there is no need for this because the basic idea is simple: a description of the (yearly) exchange of materials between the lithosphère, biosphere and technosphere or, in other words, between the immobile geological stocks, the environment and the economy. However, studies carried out at different institutes are difficult to compare because the choice of elements within the system and the categorization of the various inputs and outputs are made in different ways, and the system boundaries vary from case to case. Very recently, some initiatives have been taken in order to obtain at least an overview of the field, and if possible to take a first step on the road of harmonization of studies of this type (workshops TU Vienna, EC proposals). In Chapters 2, 3, 4 and 10, the need for and the problems of harmonization and standardization of the materials flow studies' methods and modelling are discussed.

1.4 Case studies

Case studies can be regarded as very important for methodology development. On the one hand, theories-in-development can be tested and practical problems regarding the implementation are encountered and duly solved. On the other hand it may occur that phenomena observed in case studies have an enlightening impact on theory development. Apart from facilitating methodology development, the case studies have a value of their own. The analysis of specific pollution problems as regards their origins in society provides useful insights for substance policy. The analysis of the effectiveness of certain abatement measures is also useful, because it gives a picture of which direction is a useful one to take and which is not, what can be attained with technical measures compared to volume policy, and what problem-shifting mechanisms may occur as a result of specific measures.

Two case studies are part of this thesis: cadmium and nitrogen, both on the level of the European Union, or European Community as it was at the time (EC-12, including Denmark, Western

Germany, Great Britain, Ireland, the Netherlands, Belgium, Luxembourg, France, Italy, Spain, Portugal and Greece). Through the application of the SFA method in various case studies, student research has also been important for the development. On the EC level, the student groups of 1989 and 1991 have made a contribution. These groups investigated flows of N and P; the 1989 group (Ackermans et al., 1989) on behalf of a substance deposit system on the EC level, and the 1991 group (Busschbach et al., 1991) for the design of a management plan for the North Sea. The 1992 student group (Brandenburg et al., 1992) has been involved in following the flows of nitrogen and phosphorus on the global level, to establish whether there is in fact a relationship between eutrophication in some parts of the world, and soil exhaustion in others. For all three groups, some of the results have also been used in the nitrogen case study. Individual students have contributed as well, especially Van Egmond (1990) in the case of cadmium.

Case studies have also been conducted on behalf of the Ministry of Environment in The Netherlands. These, too, have contributed to methodology development, and have been very valuable in keeping in touch with the daily reality of the careful formulations and negotiations that are an essential part of environmental policy. Two can be mentioned specifically: a study on organic chlorine compounds, in which a large group of compounds has been analyzed (Tukker et al., 1994), and a study on six heavy metals (Annema et al., 1995). Some of the results drawn from both studies are used in Chapter 4.

1.5 Contents of this thesis

Part II, consisting of Chapters 2, 3 and 4, is dedicated to SFA methodology development. In Chapter 2, a general framework for conducting studies of the SFA-type is presented, consisting of three elements: (1) the system's definition, (2) the quantification of the overview of flows and stocks, and (3) the interpretation of the results. For the system's definition some basic choices must be made, which strongly depend on the required output of the study. This is also discussed in Chapter 2. The quantification of the overview is discussed in Chapter 3 as well, linked to a discussion of different possibilities for modelling substance flows, and to a description of the computer program SFINX, which was developed during the research for this thesis. In Chapter 9, some of these aspects are revisited as a result of an evaluation of the case studies regarding the influence of some choices on the outcome. The third element of the framework, the interpretation of the results, is dealt with in Chapter 4. Two aspects are discussed: (1) the direct evaluation of the quantified overview of flows and stocks, and (2) the formulation of indicators for integrated substance chain management.

In Part III, the SFA methodology is examined from the point of view of a substance policy. In Chapter 5, five specific types of SFA applications are discussed, each with different requirements regarding system's definition, quantification, and interpretation. Chapter 6 aims at the streamlining of integrated substance chain management, by distinguishing so-called economic characteristics of substances which determine their behaviour in the economic system. With the help of these characteristics, an outline can be drafted for a sensible substance chain management strategy. The results of the case studies out of Part IV are used in this chapter to test and streamline the argumentation.

Part IV contains the two case studies. In Chapter 7, the cadmium case study is presented. Appendix 2 is written to account for the data that have been used, and to perform a sensitivity analysis regarding some of these data as well as some of the actual choices that have been made when composing the cadmium model. Chapter 8 and Appendix 3 contain the same information for nitrogen. Appendix 1 contains the results of some calculations with small theoretical systems, performed to test the various steps that must be made when designing a substance flow model. In

Chapter 9, the results of the sensitivity analyses for the case studies and the main findings of Appendix 1 are presented in a discussion regarding data and modelling choices in general.

Part V and Chapter 10, finally, are dedicated to a general discussion and to overall conclusions and recommendations.

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Workshops TU Vienna: Prof. P. Brunner of the Institute for Water Quality and Waste Management has organized two international workshops: one with Prof. P. Baccini of ETH Zürich, called *Workshop Materials Management for Regional Sustainability (MM-ARS),* April 24-28 1994, with regard to the use of materials balance studies for environmental policy; and the other called *State of the An Computer Programs for Material Balancing (SAMBA),* May 18-19 1995.

EC-proposals: various proposals for international collaboration and harmonization of materials flow studies have recently been made for the EC Program IV Environment and Climate.

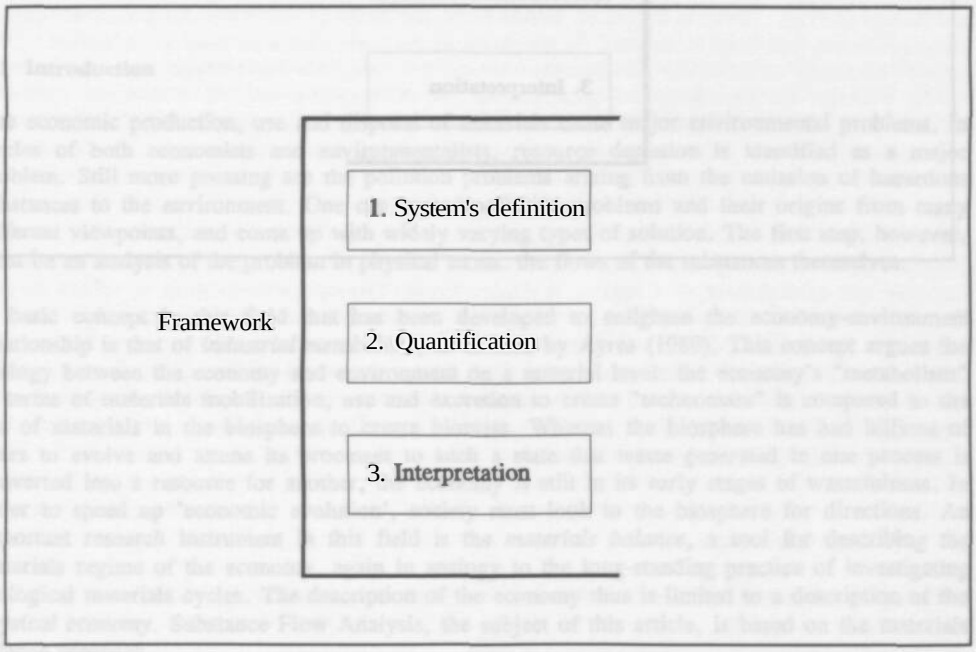
PART II SUBSTANCE FLOW ANALYSIS: A METHODOLOGY FOR STUDYING SUBSTANCE FLOWS THROUGH THE ECONOMY AND ENVIRONMENT OF A REGION

Pan II is dedicated to SFA methodology development. A general framework for conducting SFA studies is presented in Chapter 2, consisting of three elements:

- ***system's definition***
- ***quantification of the overview of flows and stocks***
- ***interpretation of the results.***

These three elements are elaborated, each in its own chapter.

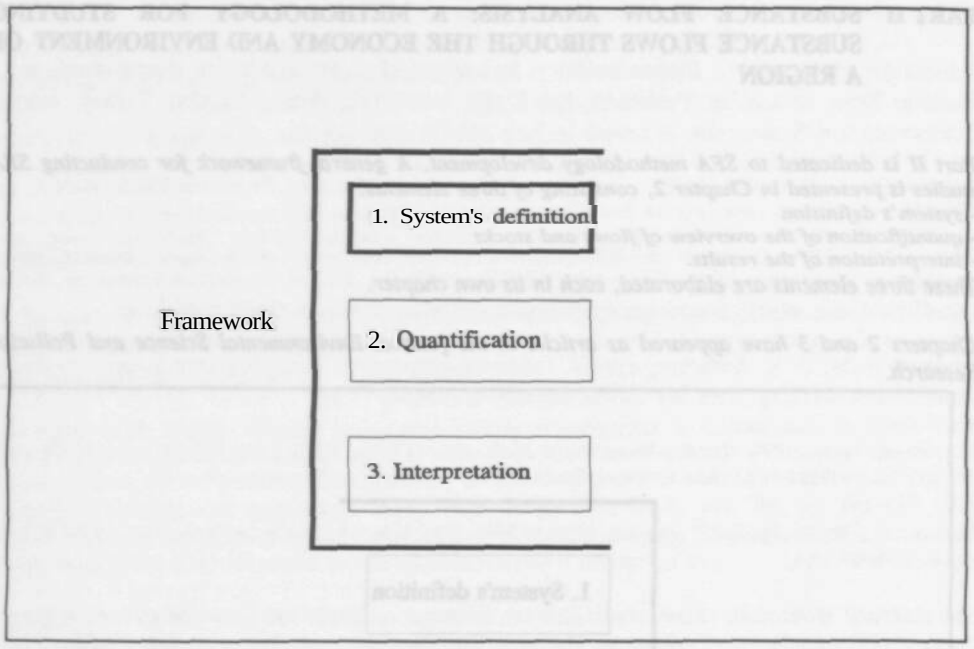
Chapters 2 and 3 have appeared as articles in the journal Environmental Science and Pollution Research.



Chapter 2 contains, apart from the general framework, a section regarding the SFA system's definition. There are four dimensions: time, space, substance, and function. The SFA system is determined with regard to time (usually, a year), space (a geographically demarcated are) and substance (one substance or a coherent group of substances. No demarcation is made regarding function.

In Chapter 3, the quantification of the overview of flows and stocks is discussed. Three possible methods of quantification are presented, each with their own possibilities and limitations: (1) bookkeeping, i.e. monitoring flows and stocks through the years, (2) static modelling, which can be used for linking environmental problem flows to their economic origins and for comparing alternative regimes, and (3) dynamic modelling, suitable for estimating the impacts of policies on the flows and stocks in future years.

The interpretation of the results is the subject of Chapter 4. A set of indicators is defined to evaluate a quantified overview of flows and stocks. These indicators refer to depletion, pollution, chain management and problem shifting.


1. System's definition
Framework
2. Quantification
3. Interpretation

CHAPTER 2 GENERAL FRAMEWORK AND SYSTEMS DEFINITION[1]

ABSTRACT

In the tradition of the study of materials flows through society, the Substance Flow Analysis (SFA) method is presented. SFA aims at providing the relevant information for a country's overall management strategy regarding single substances or coherent groups of substances. This article is dedicated to the presentation of a three-step general framework for SFA-type studies, and elaborates on its first step, the systems definition. Attention is given to the definition of the external and internal system boundaries, the categorization of the system's elements, aspects of materials choice, time, and space, and how these depend on the aim of the conducted study. Moreover, a broader discussion is started on the need for standardization of materials flow studies in general.

2.1 Introduction

The economic production, use and disposal of materials cause major environmental problems. In circles of both economists and environmentalists, resource depletion is identified as a major problem. Still more pressing are the pollution problems arising from the emission of hazardous substances to the environment. One can regard pollution problems and their origins from many different viewpoints, and come up with widely varying types of solution. The first step, however, must be an analysis of the problem in physical terms: the flows of the substances themselves.

A basic concept in this field that has been developed to enlighten the economy-environment relationship is that of *industrial metabolism,* as defined by Ayres (1989). This concept argues the analogy between the economy and environment on a material level: the economy's "metabolism" in terms of materials mobilization, use and excretion to create "technomass" is compared to the use of materials in the biosphere to create biomass. Whereas the biosphere has had billions of years to evolve and attune its processes to such a state that waste generated in one process is convened into a resource for another, the economy is still in its early stages of wastefulness. In order to speed up 'economic evolution', society must look to the biosphere for directions. An important research instrument in this field is the *materials balance,* a tool for describing the materials regime of the economy, again in analogy to the long-standing practice of investigating ecological materials cycles. The description of the economy thus is limited to a description of the *physical economy.* Substance Flow Analysis, the subject of this article, is based on the materials balance approach.

Materials balance studies have been conducted from several angles. River basin studies (Stigliani & Anderberg, 1992) have shown that the origins of water pollution have been shifting from industrial pollution to consumer emissions over the past few decades. Industry-oriented studies (Ayres et al., 1989) have raised suspicions of hidden pollution problems by signalling 'missing' amounts of materials. Another fruitful application of the materials balance approach has been to investigate the flows and stocks of individual substances or substance groups in the economy of a given region (Brunner & Baccini, 1992; Bergbäck et al., 1992). This application also allows the key flows or stocks for regulation in that region to be identified, and the effectiveness of certain

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[1] This chapter contains an article published in the journal *Environmental Science and Pollution Research:* VOET, E. VAN DER; R. KLEIJN; L. VAN OERS; R. HEIJUNGS; R. HUELE; P. MULDER: Studying substance flows through the economy and environment of a region - Part I: systems definition. ESPR vol.2 no.2, pp 89-96.

abatement measures to be assessed. The ensuing picture of the economic life cycle of a substance may be regarded as an important analytic tool for developing a regional pollution policy.

Most studies on the materials flows in a region can be described as inventories: collecting as many data as possible on flows and stocks, and organizing these in an overview that can be used to draw conclusions relevant for a materials management policy. Various attempts have been made to model substance flows, as a means of predicting the changes in materials flows resulting from given societal developments or policy measures. Most of these models are concerned with relatively small parts or suhchains (Gilbert & Feenstra, 1992), or focus on emissions and the environment (Alcamo et al., 1990). Economic Input-Output analysis, as developed by Leontief (1966), is recognized as a potentially useful technique for incorporating the sum total of all economic or societal flows in one model. Several theoretical as well as practical exercises have been undertaken in this direction (for example Kneese et al., 1972; Victor (1972) describes some more of these approaches; more recent examples can be found in Duchin (1994), Idenburg (1993) and Konijn (1993)). There is as yet no standardized methodology for conducting such studies. It could be argued that there is no need for this because the basic idea is simple: a description of the (yearly) exchange of materials between the lithosphère, biosphere and technosphere or, in other words, between the immobile geological stocks, the environment and the economy. However, studies carried out at different institutes are difficult to compare because the choice of elements within the system and the categorization of the various inputs and outputs are made in different ways, and the system boundaries vary from case to case.

The subject of this article is the Substance Flow Analysis (SFA) method, a method for the description and modelling of the flows and stocks of one substance or a group of substances in the economy and environment of a region. A discussion concerning harmonization of efforts in this field is started, especially in Section 2.2. This section contains a description of a general framework for materials flow studies and some basic choices that must be made at the start of each study. In Section 2.3, the position of SFA in this field is treated, together with the SFA system definition. Section 2.4 is dedicated to discussion and conclusions. In Chapter 3, the modelling of substance flows is discussed. Different modelling techniques are described and clarified with the help of an example system.

2.2 General framework

In general terms, materials flow studies comprise the following three-step procedure:
- definition of the system
- quantification of the overview of stocks and flows
- interpretation of the results.

All three steps involve a variety of choices and specifications, each of which depends on the specific goal of the study to be conducted, as will be argued below.

System definition

The first step in any materials flow study is to define the system. The system must be determined with regard to space, function, time and materials. If necessary, the system can be divided into subsystems. The various categories of processes, stocks and flows belonging to the system must be specified. Finally, this results in a flow chart: the specification of the *network of nodes.* In this section, some general aspects of the system definition will be treated in relation to the goal of the study.

With regard to the "space" and "function" specification, a basic choice must be made for a

"regional" or a "functional" approach (Van der Voet & Heijungs, 1994).
In the *regional* approach, the point of departure is the area itself as a geographically bounded system and what actually takes place there. The *location* determines which processes (extraction/production/consumption/waste processing) take place within the system, and to what extent. The regional approach would seem appropriate for analyzing the pollution problems of a specific area. In 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 consumption within the region; this serves as the basis for selecting the processes to be included in the system. Any relevant steps taking place outside the region must then also be included. Processes taking place within the region for the benefit of other regions (e.g. production for export) are not part of the system. As a result, a picture is not obtained of the regional environmental situation, but of the extent of the substance's life cycle and its losses to the environment *for the benefit of* the region, regardless of its location. Both approaches are relevant and both have been applied in practice. The functional approach is followed, although implicitly, in the introduction of the "ecological rucksack" concept, for example (Schmidt-Bleek, 1993).

A second general aspect concerns time. Studies on flows automatically imply a time dimension: materials flows are expressed in mass units per time unit. Generally, and also in the SFA studies conducted to date, a one-year period is chosen. This seems to be a suitable choice from the point of view of both data availability and policy formulation. In some cases a shorter time period would be more advisable, for example when the variations in time within the year are also relevant, which is well-conceivable, especially for environmental flows. In other cases a longer period would be more appropriate, for example when a slow stock-building process is being monitored.

A third choice involves the materials to be studied. Some studies follow flows and stocks of materials at a totalized level, as proposed by Kneese et al. (1972) and later by Simonis (1994) and Schmidt-Bleek et al. (1993). In others, only one substance is studied at a time (for example, Anderberg et al., 1989). Sometimes, the object is a compound material (Blaauwendraat & Van Dalen, 1993), (incorporated) energy (Odum, 1992), or coherent groups of materials (Kleijn et al., 1994). This choice, too, depends on the specific questions to be answered: totalized materials studies may provide relevant information on the "materials intensity" of a society, while one-substance studies, on the other hand, are relevant for establishing the contribution of a society to specific pollution problems.

In Section 2.3, these basic choices will be specified for the SFA method and the SFA system definition will be treated in more detail.

Quantification of the overview of flows and stocks
The quantification of the network is the next step. This involves identifying and collecting the relevant data on the one hand, and modelling on the other. Three possible ways of modelling the system are briefly discussed in this article, all three types having their own data requirements, as well as their own potential for policy support:
- bookkeeping: organizing the collected data on the identified flows and stocks into a consistent overview;
- static modelling: defining the system's flows and stocks as variables dependent on others, resulting in a set of equations to be solved for one specific year or for the "steady state" equilibrium situation;
- dynamic modelling: including in the modelling also the changes in the system's stocks and flows over time.

A bookkeeping system, although it can hardly be classified as a model, provides very relevant information for environmental policy. The input for such a system consists of data regarding the size of the system's flows and stocks of goods and materials, that can be obtained from trade and production statistics, and if necessary also data regarding the content of specific substances in those goods and materials. Emissions and environmental flux or concentration monitoring can be used for the environmental flows. A combination of those data together with application of the mass balancing principle then must lead to the desired overview of flows and stocks. The overview thus obtained may serve various purposes:

- **identifying problem flows, economic leaks or inefficiencies in materials use in a given year, thereby indicating which flows to regulate;**
- identifying potential future problems by signalling large economic stocks or increases of stock that will enter the waste stage sooner or later;
- monitoring changes in flows and stocks over the years, thereby making it possible to verify predictions, obtain an impression of the effects of certain policies or identify growing flows or stocks as potential problem flows in the future.

The bookkeeping overview may also serve as an identification system for missing or inaccurate data.

For static modelling, the most important data are variables describing the relations between the flows and stocks of the system. Emission factors, but also distribution factors over the various outputs for the economic processes and partition coefficients for the environmental compartments can be used as such variables. A limited amount of "bookkeeping" data is required as well for a solution of the set of equations. Static modelling can be used for various purposes. Two are mentioned here, both aimed at specifying the economy-environment relationship in a quantitative way:

- analyzing the causes of environmental problems by tracing back identified problem flows (or stocks) to their economic origins;
- predicting the effectiveness of pollution abatement measures, or the (side) effects on environmental problems of other measures influencing economic materials flows.

For a dynamic model, additional information is needed with regard to the time dimension of the variables: the life span of applications in the economy, the half-life time of compounds, the retainment time in environmental compartments and suchlike.
With a dynamic model, calculations can be made not only on the "intrinsic" effectiveness of packages of measures, but also on their anticipated effects in a specific year in the future, and on the time it takes for such measures to become effective. A dynamic model is therefore the most suitable for scenario analysis, provided that the required data are available or can be estimated with adequate accuracy. On the other hand, the data and modelling requirements are by far the most extensive.

Again, a choice for any one of these three types of modelling depends on the aim of the study to be conducted. In Chapter 3, modelling is discussed in more detail, together with the implementation in the computer program SFINX which has been developed as a tool for substance flow studies.

Interpretation of the results
Three types of "interpretation" are distinguished here:

1. Evaluation of the robustness of the overview quantification
2. Translating the overview into policy relevant terms
   - linking the overview to an evaluation system
   - transformations of the overview into indicators for chain management

3. Linking the overview to policy instruments.

Ad 1. Uncertainties in data may lead to uncertainties in the quantified overview. It cannot always be estimated beforehand how certain inaccuracies may influence the results. A sensitivity analysis can be conducted (case-by-case) to ascertain whether known or suspected inaccuracies undermine the results. On the other hand, accuracy is not always required to the same extent. A status quo report must give a quite accurate picture of the situation, be it on a generic level. A prediction of a future situation must be accurate enough to provide a basis for policy decisions; policy makers therefore must be able to evaluate it in terms of policy goals with regard to emissions, environmental quality, or set targets for the economic flows. For a comparison between alternative measure packages a statement regarding which package is the better one often suffices, and therefore no evaluation of the flows and stocks in an absolute sense is required. Sometimes the uncertainties in data may leave doubts as to whether absolute statements based on the overview would be valid, but will allow relative statements without difficulties.

Ad 2. The quantified overview of stocks and flows must serve as a basis for policy decisions regarding the management of substances and/or materials. Yet the overview is not always easy to evaluate in terms of policy objectives, on the one hand because it is too complicated to distill the right information, and on the other hand because additional information might be needed.
The emissions and environmental flows can be evaluated with the help of policy target, standards or objectives, in order to establish whether these flows are problematical or will be in the future. In such a case, a translation step is often required from flows to environmental concentrations.
If a group of substances is being studied, an additional step is needed to translate the flows of the different substances into comparable terms. This may be simply kg matter, as is the case with the calculations of the mass intensity of economies by Simonis (1994). In other cases, especially when the environmental risks are relevant, a conversion must be made to contributions to specific environmental problems ("acidifying potential", "global warming potential", etc., similar to the procedure used in the impact assessment step of the product Life Cycle Assessment (Guinée et al., 1993)).
Another, frequently discussed issue is the linking of the overview of flows and stocks to some sort of economic model. This may take a wide variety of forms, from introducing economic parameters for calculating the pathways of the flows and stocks, through linking the flows model to an economic evaluation model, to adding materials flow overviews to the System of National Accounts. This issue is both highly relevant and extremely complicated, as is reflected in the fact that after decades of discussion little progress has been made on implementing operational systems.

A powerful help for the evaluation of the overview is the definition of indicators (Kuik & Verbruggen (eds.), 1991). Indicators can be selected from the overview, by singling out a specific flow or stock as the relevant one to follow, or they can be calculated directly from the overview. Indicators may be defined for environmental flows and/or stocks, as an addition to the numerous environmental quality indicators already existing. In this field, an indicator that can be calculated from the overview has for example been developed for the problem of eutrophication (Weterings & Opschoor, 1992). Rather less numerous are indicators for the economic substance flows, which could be called indicators for integrated chain management and have bearing on the (possible, future) losses from the economy to the environment, or in other words the leaks out of the economic cycle. In this field, the overview of economic stocks and flows could contribute in an important manner. To mention a few possibilities: the already mentioned economy's materials intensity, the economic throughput, the efficiency of groups of processes, the secondary vs. the primary materials use, the economic accumulation all can be calculated from the overview and could serve as indicators for the metabolism of the society. A third possibility is the identification

of indicators for the system as a whole. We could think here for example of comparing the magnitude of the economic cycle of a certain substance with that of the natural cycle, to have some sort of indication of the potential risk (Huele et al., 1993). This goes in the direction of the study of biogeochemical cycles and their transformation by man's activity into anthropo-biogeochemical cycles (Schlesinger, 1991; Walker, 1991).

Ad 3. In some cases, the overview is prepared with the aim of linking it to a specific policy instrument, which poses its own specific requirements. An example of this is the mineral bookkeeping practised by farmers in the Netherlands to obtain insight into the mineral losses resulting from their agricultural operations. In the future, this bookkeeping overview may be linked to a mineral surplus tax (Bernts et al., 1993). Another example is the Substance Deposit system (Huppes et al., 1992), which is rather like the surplus tax but would be operated on a national or supra-national level.

The third step of the framework, the interpretation of the results, will not be treated further in this article. In Chapter 4, the interpretation of the SFA quantification is treated in more detail.

2.3 SFA System definition

As mentioned in Section 2.2, the choices regarding both system definition and the most suitable type of modelling depend on the aim of the study. The general aim of the conducted SFA studies, for which the method presented here has been developed, can be specified as: *to provide the relevant information for a region's management strategy regarding specific pollutants.* This leads to two basic choices, substantiated by the starting point of the pollution problems as they present themselves within the region:
- the choice for the regional approach;
- the choice for one substance or a limited group of substances to be analysed at a time.

Space, time and materials
The first demarcation to be made is a geographical one: the choice of a region. Such a choice often follows naturally from the goal of the study. In general, there are no real requirements for the region's size: any size from purely local (e.g. 1 hectare) to global is possible. A choice for an administrative region such as a country or a group of countries has definite advantages, especially with regard to data availability (production and trade statistics). It also facilitates a linkage with a country's environmental policy. Other choices are possible, from the point of view of environmental analysis (river basins, coastal seas), or otherwise (counties, polders, agricultural units). The inclusion of various scale levels within one study may also yield relevant information.
The choice for the materials to be investigated has been inspired, in the SFA studies conducted in the past, by established environmental problems within the region. Another possibility is a choice for economic bulk flows such as iron and steel, aluminium or (fossil) carbon.

For the remainder, the SFA system definition is derived from three basic notions regarding the relationship between the economy and the environment:
- the economy/environment distinction
- the economy/environment analogy
- the economy/environment integration.

Figure 2.1 represents the SFA system in its most general terms.

The economy/environment distinction
Differentiation into subsystems is not required for the modelling of substance flows, but it is

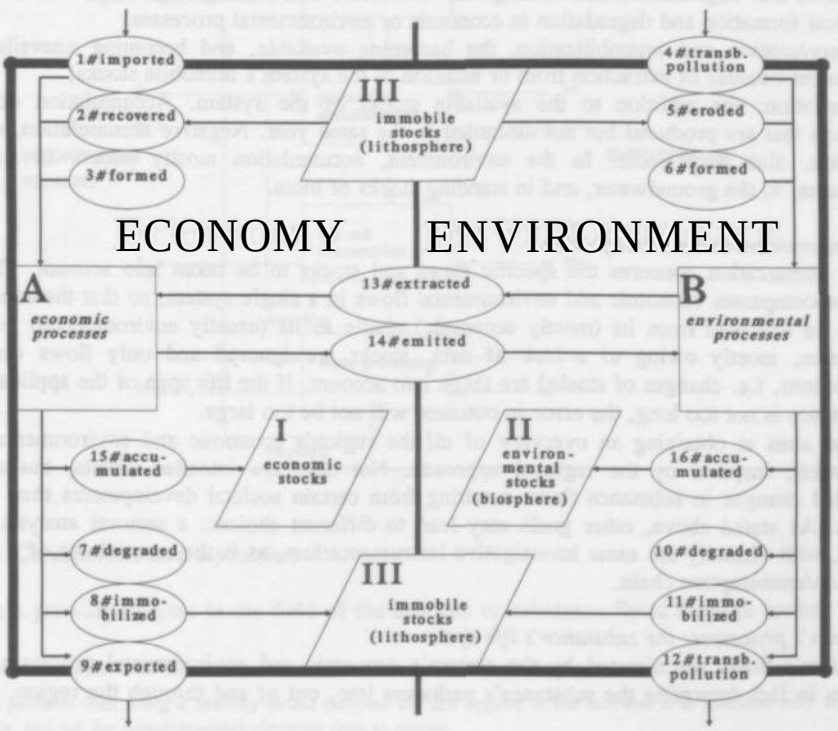
useful for interpreting the results in terms of the economic-environmental interaction. Two subsystems are acknowledged:

- the societal subsystem, also referred to as the economy, or (also used) the technosphere or the anthroposphere. This subsystem contains the stocks and flows mainly controlled or caused by humans;
- the environmental subsystem, also referred to as the biosphere. This subsystem contains the stocks and flows in the environment that can be described as biologically available.

The immobile stocks, encompassing the geological stocks in the geosphere or lithosphère, could be defined as a third, separate subsystem, with its own flows and processes (be it on a geological time scale) and its own exchanges with the other two subsystems. Isolation from the economic or environmental surroundings is then the key criterion for characterizing stocks as immobile. Another possibility is to define the immobile stocks as a category of stocks within the other two subsystems, since scrutinizing the actual geological processes will hardly ever be relevant in SFA practice. The geological stocks, as well as some environmentally harmless, inert bulk stocks such as atmospheric nitrogen gas and NaCl in the sea, or specific forms of long-term storage in the economy could then be encompassed. In Figure 2.1 these are pictured on the border between the economy and environment, because both certain economic and certain environmental stocks could theoretically be described as immobile stocks.

It is, of course, also possible to divide both subsystems into further subsystems. Husar (1994) for example distinguishes the biosphere, atmosphere and hydrosphere as subsystems of the environment. Within the economy, a distinction can be made between the various stages of a substance's life cycle, for example, or between the intentional and the unintentional flows of a substance. The usefulness of such subdivisions once again depends on the goal of the conducted study.

Figure 2.1 The Substance Flow Diagram



Actually drawing the borderline between the economy and environment inevitably leads to practical problems. Arguments can be found, for example, for viewing "landfill" as an emission to the environment, but also for keeping the landfill facility itself within the economy and counting only the losses from this landfill as emissions. Agricultural soil may be considered a part of the production system and therefore part of the economy, but may also be looked upon as an environmental compartment. In the latter case, application of fertilizer counts as an emission, while in the first case only the losses from agricultural soil to the atmosphere or groundwater qualify as emissions. It may depend on the aim of the study how exactly the demarcation is specified, as long as the specification is clear and is followed through in all its consequences.
In specific cases, it may be sufficient just to take one subsystem into account. Modelling only the economic flows, for example, will be adequate when the goal of the study is to establish whether certain emissions may be expected to be reduced to a specific level. In the case of overall substance management, however, it is useful to consider both subsystems: relevant information can be obtained on the magnitude of the economic flows relative to the environmental flows, and a relation may be established between environmentally problematical flows and the economic flows that cause them.

The economy/environment analogy

The economy/environment analogy as a criterion for the system definition originates directly from the concept of industrial metabolism. The Substance Flow Diagram (SFD) shows this analogy by specifying the subsystems inflows as well as outflows in corresponding terms:

- import/inflow and export/outflow: flows entering the region from, or leaving the region to, neighboring regions. In the economy, this concerns the import and export of the substance in raw materials, goods and waste products; in the environment, this is the transboundary in- and outflow via air or surface waters;
- formation and degradation: the coming into existence, and ceasing to exist, of substances by chemical formation and degradation in economic or environmental processes;
- recovery/erosion and immobilization: the becoming available, and becoming unavailable, of substances because of extraction from or addition to the system's immobile stocks;
- accumulation: the addition to the available stocks of the system. Accumulation occurs in products that are produced but not discarded in the same year. Negative accumulation, or stock decrease, also may occur. In the environment, accumulation mostly occurs in soils and sediments, in the groundwater, and in standing stocks of biota.

The economy/environment integration

Another demarcation concerns the specific flows and stocks to be taken into account. The SFA method encompasses economic and environmental flows in a single system, so that the substance's fate can be followed from its (mostly economic) cradle to its (usually environmental) grave. In many cases, mostly owing to a lack of data, stocks are ignored and only flows (including accumulations, i.e. changes of stocks) are taken into account. If the life span of the applications of the substance is not too long, the error in outcome will not be too large.
SFA also aims at obtaining an overview of *all* the region's economic and environmental flows (and stocks), inspired by the regional approach. Not only the intended effects, but also the unintended changes in substance flows resulting from certain societal developments then become apparent. As stated above, other goals may lead to different choices: a sectoral analysis is also possible, with virtually the same investigative instrumentarium, as is the scrutinizing of a specific production/consumption chain.

The system's processes: the substance's life cycle

The system's flows are directed by the system's economic and environmental processes. These processes in fact determine the substance's pathways into, out of and through the region, and are

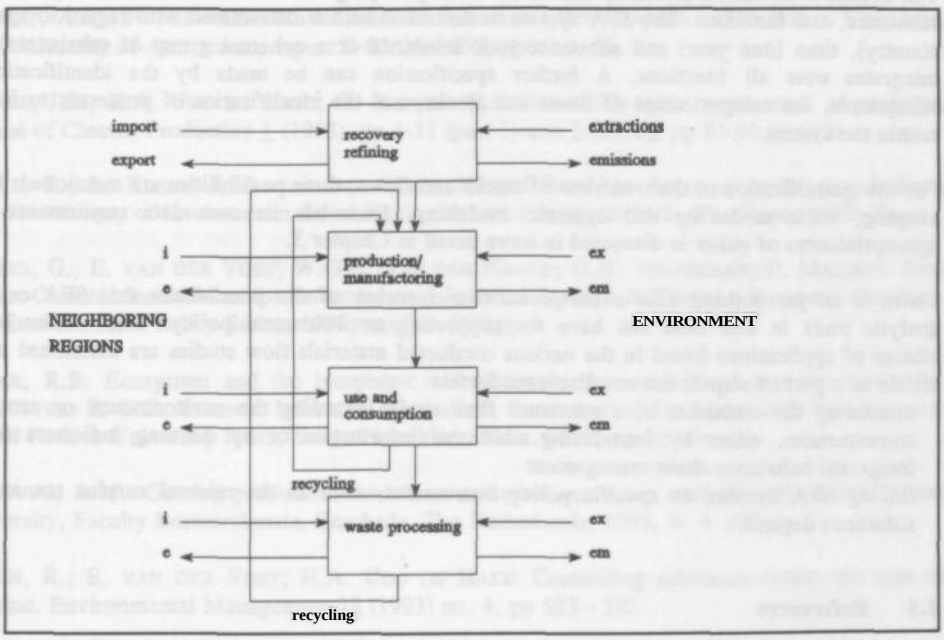
therefore the main object for modelling. Each process, economic or environmental, is described in terms of a redistribution of flows. Together, these processes and the flows that connect them provide a *network of nodes,* describing the substance's life cycle from cradle to grave.

A great deal of modelling has been performed on the environmental processes: atmospheric dispersal, evaporation, leaching, run-off, bio-accumulation, etc. This has even led to some very generalized models of the total environment, describing the exchange between the environmental compartments, such as the multimedia Mackay models (Mackay & Clark, 1991). In *fact,* such a multimedia type model could very conveniently be incorporated in a general SFA model for the environmental flows[2].

For the economic flows, no such model presents itself. The sectoral Input-Output modelling developed by economists offers the greatest possibilities, but also has some drawbacks. Nonetheless, the I-O systems approach, with the sectors as processes or nodes and the mutual deliveries as flows, can very well be used for SFA purposes. This will be treated in more detail in the follow up article.

The economic processes together describe the substance's economic life cycle. Such a life cycle can be summarized as in Figure 2.2. Each of the life cycle stages is represented by a number of linked nodes (sectors or processes).

Figure 2.2 The substance's economic life cycle.



2.4 Conclusions and discussion

There is a growing interest in the field of the analysis of substance flows through society and the

[2] One problem with using a Mackay model (adapted for the region) is the fact that it is intended only for organic compounds, and not for non-degradable elements such as metals.

environment, and the use that can be made of these studies by environmental policy design. So far, there has been little attention for harmonization of these efforts. In this article it is stated that the aim of each specific study determines the choices regarding systems definition and appropriate type of modelling. Therefore, it would not be possible to agree on one standard methodology for all studies of this type. This does not mean that no general rules can be identified. The framework stated in Section 2.2 is presented as a procedure for materials and substance flow studies in general. This general framework could be the starting point for a general discussion on the question, which choices consequently have to be made, how those choices would be affected by the aim of the study to be conducted, and what the implications are for the conclusions can be drawn by policy makers. This framework constitutes of three steps:

1. definition of the system
2. quantification of the overview of stocks and flows
3. interpretation of the results.

In this article, the discussion is started by specifying these choices for the here presented Substance Flow Analysis (SFA) method, and indicating in which cases these choices would be made differently. The goal of SFA is defined as: to provide the relevant information for a region's overall management strategy with regard to one specific pollutant or a limited group of pollutants.

The system's definition primarily has to do with specifying the four basic variables: space, time, substance, and functions. The SFA system as described here is determined with regard to space (a country), time (one year) and substance (one substance or a coherent group of substances), but integrates over all functions. A further specification can be made by the identification of subsystems, the categorization of flows and stocks, and the identification of processes to include within the system.

For the quantification of the overview of stocks and flows, three possibilities are mentioned: book-keeping, static modelling and dynamic modelling. Each has its own data requirement. The appropriateness of either is discussed in more detail in Chapter 3.

There is as yet nothing near a comprehensive overview of the possibilities that SFA or other analytic tools in this field can have for supporting environmental policy. Two, rather broad, classes of applications found in the various conducted materials flow studies are mentioned in this article as a part of step 3, but not discussed further:

- evaluating the outcomes of a substance flow study regarding the environmental or economic consequences, either by introducing additional information or by defining indicators for an integrated substance chain management
- linking SFA systems to specific policy instruments, such as the mineral surplus tax and the substance deposit.

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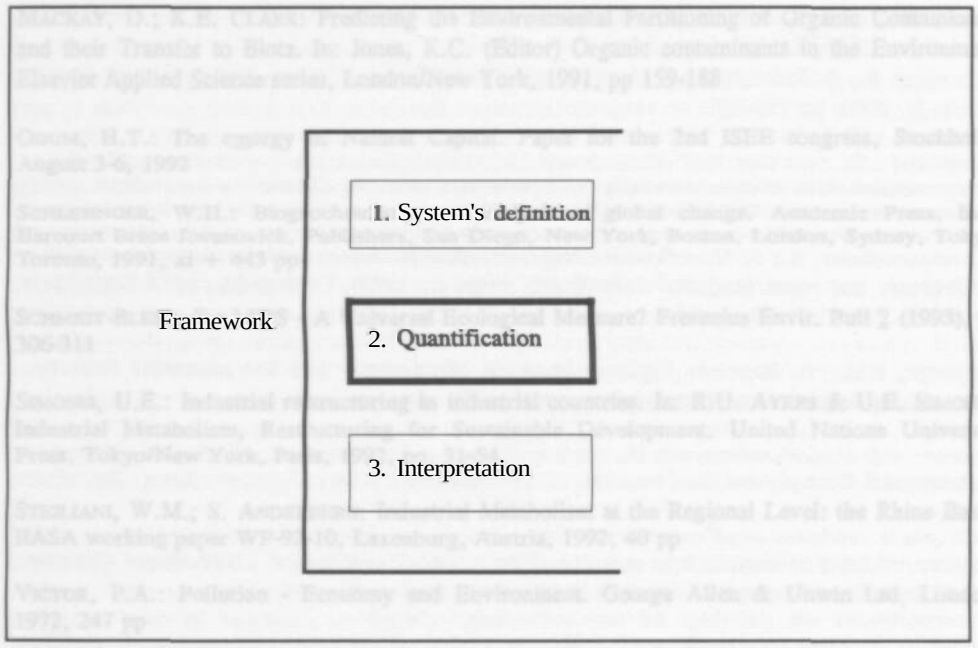
Framework
1. System's definition
2. Quantification
3. Interpretation

CHAPTER 3 MODELLING - QUANTIFICATION OF THE OVERVIEW OF FLOWS AND STOCKS[1]

ABSTRACT

In the tradition of the study of materials flows through society, the Substance Flow Analysis (SFA) method and its software tool SFINX are presented. SFA aims at providing the relevant information for a country's overall management strategy regarding single substances or coherent groups of substances. Three modelling techniques and their possibilities and limitations are discussed: bookkeeping, static modelling, and dynamic modelling. The computer program SFINX can be used for various purposes: (1) to obtain an overview of stocks and flows of a substance in, out and through a nation's economy and environment for a specific year, (2) to trace the origins of specific pollution problems, and (3) to estimate the effectiveness of certain abatement measures. Each application has its own requirements with regard to data and modelling.

3.1 Introduction

In Chapter 2, the Substance Flow Analysis (SFA) method was discussed. A general framework for conducting SFA-type studies was presented, that consists of three steps: systems definition, quantification of the overview of stocks and flows, and interpretation of the results. The first step, the systems definition, has been discussed. The subject of Chapter 3 is the second step of the framework: the quantification of the overview, or in other words the modelling of substance flows and stocks. The computer program SFINX (Substance Flows modelled by InterNodal exchange), developed at the Centre of Environmental Science of Leiden University as a tool to support SFA studies and applied in a number of case studies (Van der Voet et al., 1994 (1) and (2); Van der Voet et al., in press, Kleijn et al., 1993), will be used to illustrate the possibilities described below. The flows and stocks of one substance in a simple system representing a region with only three processes, as pictured in Figure 3.1, will be analyzed to clarify the theoretical argumentation regarding modelling techniques. In the case studies conducted to date, the systems comprise 15-30 sources and as many sinks, 20-50 distribution processes or nodes (of which less than 10 environmental nodes), and up to 400 variables (flows and stocks). No attempt is made to describe flows and stocks of a real substance, distributed by real economic and environmental processes, in a real year and a real region. Moreover, no attempt is made to comment on the first and third step of the framework, the system's definition and the interpretation of the results.

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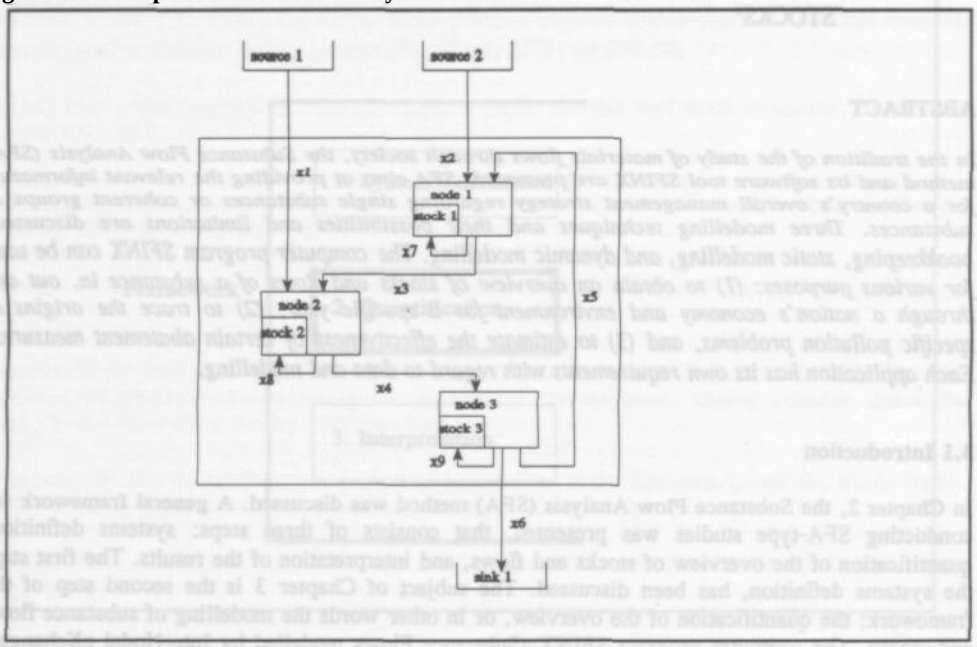
[1] This chapter contains an article published in the journal Environmental Science and Pollution Research: VOET, E. VAN DER; R. HEIJUNGS; P MULDER; R. HUELE; R. KLEUN; L. VAN OERS: Studying substance now» through the economy and environment of a region - Part II: Modelling. ESPR vol.2 no.3 pp 137 - 144, 1995.

Figure 3.1 A process network: the system EXAMPLE.



This system has two sources and one sink. Within the system, there are three nodes. The nodes each contain a certain stock (s_1, s_2 and s_3, expressed in kg substance). There are six flows connecting the sources, nodes and sink (x_1 to x_6, in kg substance/year). The variables x_7 to x_9 (also in kg substance/year) represent additions to (or extractions from) the nodes stocks.

After the description of the system in terms of nodes, sources, sinks and connections according to the procedure outlined in Chapter 2, a quantification is in order: the size of the various stocks and flows, always expressed in terms of the substance or substance group under study, in an absolute sense and relative to each other. Three possible ways to achieve the quantitative overview are discussed below, accompanied by the SFINX-example for clarification:
- bookkeeping
- static modelling
- dynamic modelling.

These will be treated separately in Sections 3.3 to 3.5. First, though, in Section 3.2, a short description of the general procedure of SFINX is given, i.e. independent of the type of modelling selected.

3.2 General description of SFINX

SFINX can be used as a bookkeeping program and as a static model. In other words, on the one hand SFINX can be used to specify the system's processes and calculate the magnitude of flows and stocks based on data regarding the flows and stocks themselves. On the other hand, flows and

stocks can be calculated from the distribution characteristics of processes, i.e. the quantitative relations between flows and stocks. SFINX makes use of an external mathematical program; it functions on a 386 PC under DOS (van Oers et al, 1995).

The first step is the implementation of the network of nodes defined beforehand. It is possible in SFINX to:

- **define sources, sinks and nodes: the distribution processes;**
- **establish named connections between two different nodes: the flows;**
- **establish a named connection from and to a single node: the stocks;**
- add tables to certain nodes, representing the data from which the magnitude of certain flows or stocks is calculated (for example, a list of products with their respective content of the substance under study, multiplied and added to give one figure);
- specify the relations between the system's flows and/or stocks with formulae.

To every specified flow and stock an equation is added, based on either a fixed value (by table, $x_1 = y_1$, *or* directly, $x_1 = 20$), or a formula describing a dependency on other flows or stocks fo $= 0.2 \times (x_2 + x_3)$; however a condition for a good solution is the indication of one and only one flow per node as a balancing item. The choice of the balancing item is of crucial importance and depends on the specific use of SFINX. This subject will be treated in more detail below.

This basic file, containing all relevant information, is translated into a clean set of equations which serves as an input for the external mathematical program and is subsequently solved. The outcome can be imported again in SFINX and can be viewed in various shapes.

3.3 Bookkeeping

The first way to "model" the system is to treat it as a bookkeeping system. If available, data on the magnitude of flows and stocks are used. Missing amounts can be estimated by applying the mass balance principle. In this way, inflows and outflows are balanced for every node as well as for the system as a whole, unless accumulation within the system can be proven. This technique is most commonly used in materials flow studies, and can be viewed as a form of descriptive statistics (Olsthoorn, 1993; Bernts et al., 1993; Fleckseder, 1992; Doluschitz, 1992; Harenz, 1992). If applied to the description of societal flows, in most of the cited practical applications the stocks are ignored, and data collection is concentrated on flows only. In fact, the technique for this is rather similar to drawing input-output tables of mutual deliveries between economic units. There are, however, some examples of case studies that specifically address societal stocks (Lohm, 1994) and use these as an indicator for possible environmental problems in the future.

SFINX can be used as a bookkeeping program. The reproduction of a situation in a previous year would be the aim. SFINX then serves as a tool to structure the data on the flows and stocks of a substance. In this case much use is made of the table function, since most flows will be calculated from statistical and monitoring data.

For the economic flows, these data consist mainly of two elements:

- quantitative data on raw materials, products and waste streams. Trade and production statistics are an important source. Other flows are estimated by specific waste treatment oriented studies and registrations of emissions;
- quantitative data on the content of the substance in raw materials, products and waste streams. Depending on the product and substance, the content may vary from a full 100% to a mere trace.

On the environmental side, environmental monitoring data are valuable for the quantification of the system. Examples of these are: emission registration, riverine and atmospheric loads monitoring, run-off and leaching measurements and suchlike.

Obtaining data on materials flows in the economy is not easy. Data on trade (im- and export) and on production can generally be traced in statistical publications, with varying difficulty. Data on consumption or use, and especially on the size of economic stocks are scarcely available, if at all.

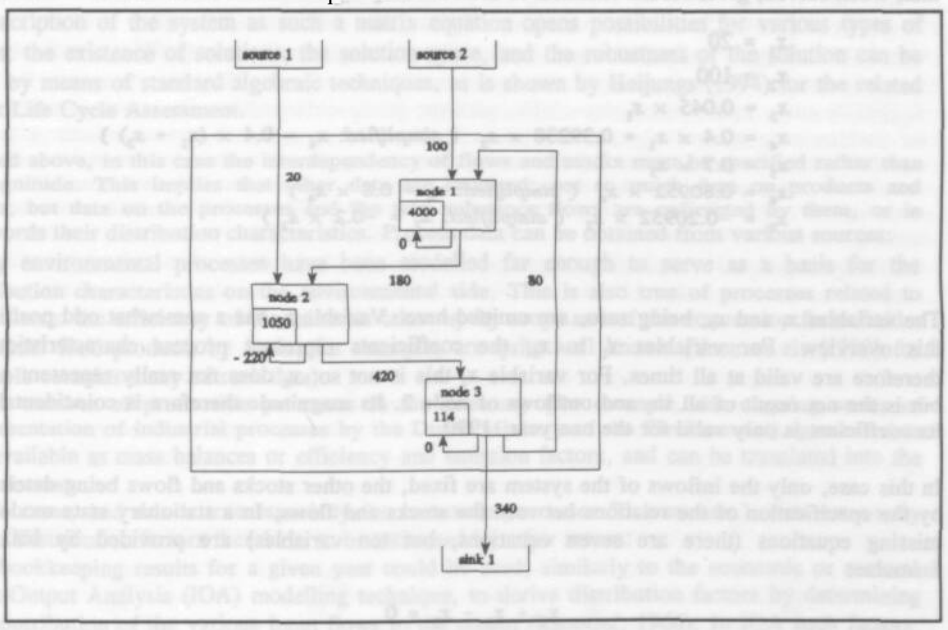
SFINX requires each node to have one balancing item. For SFINX as a bookkeeping program, this can be used in various ways. A balancing item may serve as a first estimate for a flow for which no data are available. A balancing item may also be used to examine the correctness of the magnitude of the flows, if all in- and outflows of a node can be derived from data. If a node is really off-balance, often a missing flow can be suspected, or sometimes the data may prove to be inaccurate. A balancing item may also be used to estimate the accumulation of a substance in a certain node. Regarding accumulation and stock building, especially within the societal subsystem, data are hardly ever available. Finally, a balancing item may be used as a "deficit" post, merely signalling data inconsistencies without trying to smooth them over.

The data are organized in tables and assigned to flows or stocks. Together with the balancing requirement, this would lead to the following set of equations:

$x_1 = y_1 = 20$
$x_2 = y_2 = 100$
$x_3 = y_3 = 180$
$x_4 = y_4 = 420$
$x_5 = y_5 = 80$
$x_6 = y_6 = 340$
$s_1 - y_7 = 4000$
$s_2 = y_8 = 1050$
$s_3 = y_9 = 114$
$x_2 + x_5 - x_3 - x_7 = 0$
$x_1 + x_3 - x_4 - x_8 = 0$
$x_4 - x_5 - x_6 - x_9 = 0$

Variables x_7, x_8 and x_9 serve as balancing items. Solution of the system, as pictured in Figure 3.2 below (numbers representing mass flows per year), proves that x_7 and x_9 equal 0, but x_8 = -220. This means that nodes 1 and 3 are balanced, but node 2 is not: a negative accumulation or stock decrease takes place in node 2. By treating this technically as a sink, an outflow out of the system, a state of balance is simulated which makes it possible to solve the equations. In the overview, the system's stocks appear with fixed magnitudes. In fact, one of the stocks (s_2) is decreasing over the year. In the bookkeeping report of next year, this stock is then fixed at a lower level.

Figure 3.2 The network of nodes quantified.



This system cannot be used to calculate variations in flows and stocks. A change in one flow does not influence the other flows, with the exception of the balancing item. In reality, flows are not fixed but depend on one another in various ways. The system can be used, however, as a monitoring instrument, to follow the "state of the flows and stocks" over the years. In this way, variations in flows and stocks become visible *after* the events that have caused them, and thus the impact of measures or other developments can be evaluated afterwards.

3.4 Static modelling

In the case of static modelling, the process network is translated into a set of equations describing the flows and stocks as dependent on one another. In order to do so, the relations between the various stocks and flows must be specified. Data on the relations between the stocks and flows are more important than data on the stocks and flows themselves, and the modelling outcome is determined largely by the distribution pattern. Only a limited number of fixed data is required. This will be treated in more detail below, in the elaboration of the SFINX example. In the case of static modelling, the set of equations is solved by assuming a stationary state, i.e. a state in which the flows are invariable over time. This kind of static modelling has its limitations, but also its advantages compared with the more sophisticated dynamic type of modelling. On the one hand, the stationary state outcome cannot be used for predictions of any situation in a given year in the future, or of the time span involved in reaching it. On the other hand, far less data are required and the outcome, within its limitations, is rather more robust because many uncertainties are excluded. Static models have been applied by Schr0der (1994), Bader (1993) and also, for modelling purely environmental flows, for example by Mackay & Clark (1991).

The process network with its stocks and flows can be translated into a concurrent set of equations

that, when solved, gives results identical to the bookkeeping overview:

$x_1 = 20$
$x_2 = 100$
$x_3 = 0.045 \times s_1$
$x_4 = 0.4 \times x_1 + 0.39238 \times s_2$ (*simplified:* $x_4 = 0.4 \times (x_1 + s_2)$)
$x_5 = 0.7 \times s_3$
$x_6 = 0.8O952 \times x_4$ (*simplified:* $x_6 = 0.8 \times x_4$)
$x_8 = -0.20952 \times s_2$ (*simplified:* $x_7 = -0.2 \times s_2$)

The variables x_7 and x_9, being zero, are omitted here. Variable x, has a somewhat odd position in this overview. For variables x_1 to x_6, the coefficients represent process characteristics and therefore are valid at all times. For variable *x,* this is not so: x_8 does not really represent a flow but is the net result of all in- and outflows of node 2. Its magnitude therefore is coincidental, and its coefficient is only valid for the one year, 1990.

In this case, only the inflows of the system are fixed, the other stocks and flows being determined by the specification of the relations between the stocks and flows. In a stationary state model, the missing equations (there are seven equations, but ten variables) are provided by balancing formulae:

$$x_2 + x_5 - x_3 = 0$$
$$x_1 + x_3 - x_4 - x_8 = 0$$
$$x_4 - x_5 - x_6 = 0$$

This set of equations can be represented as a matrix equation, provided that, as in this case, all equations are linear:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.045 & 0 & 0 \\ -0.4 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.4 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.7 \\ 0 & 0 & 0 & -0.8 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0.2 & 0 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & -1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} xf \\ x2 \\ x3 \\ x4 \\ x5 \\ x6 \\ x8 \\ s1 \\ s2 \\ s3 \end{bmatrix} = \begin{bmatrix} 20 \\ 100 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

or more compactly:

$$A \quad x = y$$

The description of the system as such a matrix equation opens possibilities for various types of analysis: the existence of solutions, the solution space, and the robustness of the solution can be studied by means of standard algebraic techniques, as is shown by Heijungs (1994) for the related product Life Cycle Assessment.

As stated above, in this case the interdependency of flows and stocks must be specified rather than the magnitude. This implies that other data are required: not so much data on products and contents, but data on the processes and the way substance flows are redirected by them, or in other words their distribution characteristics. Process data can be obtained from various sources:

- Many environmental processes have been modelled far enough to serve as a basis for the distribution characteristics on the environmental side. This is also true of processes related to agriculture: the efficiency of the minerals taken up by crop, and of the conversion from fodder to animal food products by cattle, for example, are quite well known (Veen et al. (1993) for example contains many of such data).
- For a number of production processes in the economy (for example, the ongoing series of documentation of industrial processes by the Dutch Ministry of the Environment), process data are available as mass balances or efficiency and emission factors, and can be translated into the right format.

In other cases, and this is true especially for economic processes "downstream", data are sorely lacking. Distribution factors then have to be estimated by other means:

- The bookkeeping results for a given year could be used, similarly to the economic or sectoral Input-Output Analysis (IOA) modelling technique, to derive distribution factors by determining the contribution of the various input flows to the output (Leontief, 1966). In IOA such factors, directly calculated from the Input-Output table for a given year, are called technical coefficients. In SFA practice it is often more useful to determine the division of the input over the various output flows, which could be described as "reversed technical coefficients" or output coefficients. Schrøder (1994) introduces the concept of "performance variables" (PVs), which could be derived as such output coefficients, but could also be composed out of other information. These PVs can be used to comment on the efficiency of the process they refer to.
- The mass balancing principle can be used to estimate a missing flow by appointing it as a balancing item. This has been applied in case studies, especially for estimating unknown but large quantities of generated solid waste and flows from producers to consumers.

A limited but adequate number of stocks or flows must be fixed, however, to be able to solve the set of equations. These given flows together then determine the magnitude of all the others. It depends on the purpose of the analysis which variables should be selected as the fixed variables.

SFINX can be used as a static model. As such, it has been applied in the case studies referred to before. It has been used for two specific purposes: to analyze the origins of certain pollution problems, and to estimate the effectiveness of certain policy measures.

Origins analysis

For a pollutants policy, insight into the origins of pollution problems is essential. The origins of one specific problematical flow can be traced at several levels. In the conducted case studies, three levels are distinguished:

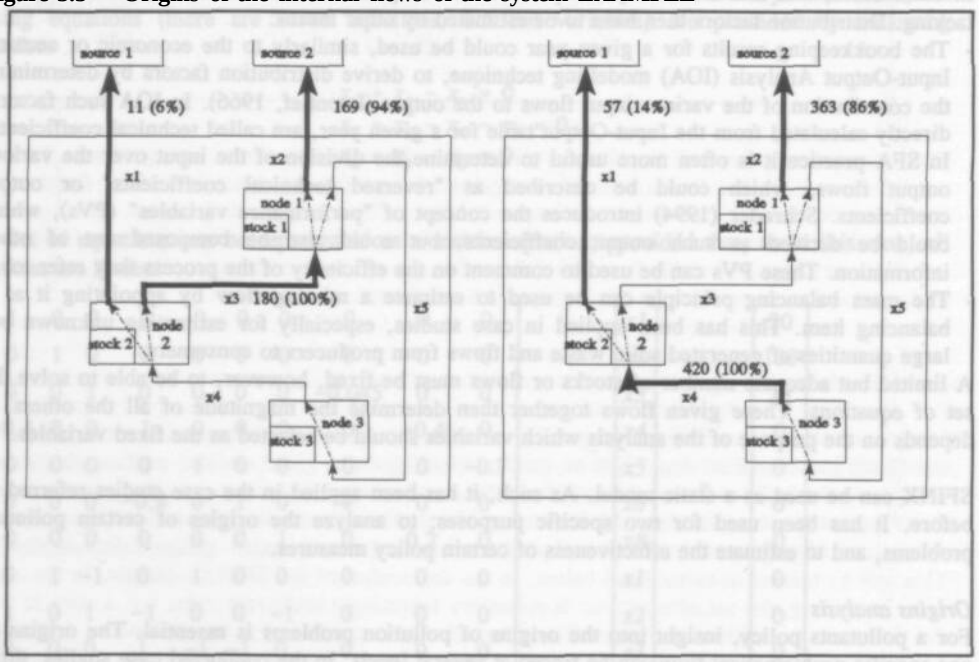
- direct causes, derived directly from the nodes balance (for example, one of the direct causes of the cadmium soil load is atmospheric deposition);
- the economic sectors, or environmental policy target groups, directly responsible for the problem, identified by following the path back from node to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

- ultimate origins, found by following the path back to the system boundaries (for example, the import of zinc ore is one of the ultimate origins of the cadmium soil load).

The SFINX origins analysis is aimed at the ultimate origins as the most difficult to trace, mainly because of the looped processes that occur within the system. For this purpose, the set of equations of the SFINX model is used in reverse: the specific problem flow is expressed in terms of the fixed variables. From this it follows that for this purpose, all system inflows and nothing but the system inflows of the SFINX model must be appointed as the fixed variables. All other flows are then dependent, either directly or indirectly, on the inflows. In some cases, this may run contrary to our perception of causality, but it is a necessary condition for a successful origins analysis.

The origins analysis is made for a specific year. The set of equations, when solved, must therefore lead to an overview that is identical to the "bookkeeping" overview for the same year. The bookkeeping overview thus serves as a check, but could also be used to derive formulae, as described above. To explain the procedure once again the example system is used. In solving the set of equations, the two inflow formulae (determining x_1 and x_2) are cancelled, and all other variables are written in terms of x_1 and x_2. The outcomes can be viewed with help of the SFINX-menu. Figure 3.3 shows the network of processes with, for each of the internal flows, a specification of its origins.

Figure 3.3 Origins of the internal flows of the system EXAMPLE



In absolute figures as well as in percentages, the contribution of the two sources to the selected flows is specified. From the above, it appears that source 2 contributes most to all internal flows, but not to the same degree in every case. In percentages, source 1's contribution to x_4 is two-and-a-half times as high as its contribution to x_3, in absolute figures this is five times. For a pollution policy, this provides relevant information: it indicates which sources must be influenced in order to solve the problem.

The effectiveness of measures

As stated before, with a static model it is impossible to obtain a picture of the effects of certain measures for a specific year in the future, proceeding from the situation in the present or a recent past. It is, however, eminently possible to gain an insight into the effectiveness of some measures compared to others, or compared to doing nothing. This can be achieved with SFINX by calculating the stationary end state as a result of a certain materials management regime, and comparing this with the stationary end state as a result of certain changes in the regime. This type of modelling is called "comparative static modelling" and has well-known applications in econometric modelling (Chiang, 1967). In this case, a steady state is no longer simulated by treating accumulation as an outflow. Instead, accumulation is eliminated. SFINX then calculates the stationary end state resulting from the current regime by calculating the magnitude of the node's stock for which, given the set of equations, IN equals OUT. Policy measures influencing the substance flows are translated into changes in the set of equations. The stationary end state resulting from this new regime can then be compared with the stationary end state of the current regime in order to comment on the usefulness of the measures in principle. In addition to the data specified for the origins analysis, data are required with regard to:

- the measures or measure packages, to be translated into changes either of the fixed variables or of the distribution factors;
- external factors, such as population growth, to be translated into changes either of the fixed variables or of the distribution factors.

When modelling the substance flows with the aim of calculating the effectiveness of measures or policies, the best results may be achieved by paying attention to causality as much as possible. This means that the system's sources do not automatically count as fixed variables. Instead, a certain production level (supply for external markets) or a use level (demand, or "stock-in use") could be fixed at a specific level. This use level then determines the production and/or import level, as well as the waste disposal quantities; variables are calculated with the use flow as a starting point, instead of the source flow. Changes in regime may affect the fixed variables, for example by lowering the fixed production or use level. This could be a translation of a specific volume policy. On the other hand, the formulae may be changed, for example by increasing the efficiency of a process, or the relative losses from stock by increasing the life expectancy of certain applications: this would be a translation of technical measures directed at economic production or waste disposal processes.
In this way, it becomes possible to use SFINX as an optimizing tool as well: to select the measure or measure package that leads to the best overall result.

In Table 3.1, the example system once again is used for clarification. The current situation, the stationary end state as a result of the current regime, and the stationary end state as a result of a changed regime are presented alongside one other. Regime changes appear in two places: one of the inflows is lowered, and in one of the formulae (x_3) the outflow as a fraction of the stock is lowered. In policy terms, this could for example be the result of a decrease in the use of the substance on the one hand (volume policy), and an increase of the durability of the application on the other (technical measure).

The stationary end state of the current regime, as it appears, differs from the present situation: the stock decrease (x_7) has been erased, resulting not only in a smaller stock s_2 but also in reduced stocks s_1 and s_3. The systems sink is back to the equilibrium level of the total of the systems sources (120), and the internal flows have stabilized at a somewhat lower level. The stationary end state of the changed regime, visible in the right column, indicates that the changes lead to smaller flows compared to the current regime. The equilibrium level of stock s_1, however, appears to be much larger than the current one. This is caused by the decreased relative output of the processes node 1 represents: the distribution factor of 0.045 now is down to 0.0045. Dependent on the

desired changes, the new regime can be evaluated as beneficial or not.

Table 3.1 Comparison of current situation, the stationary end state of the current regime, and the stationary end state of a modified regime.

current situation	current regime, stationary end state	new regime, stationary end state
(* formulas *)		
$x_1 = 20$	$x_1 = 20$	$x_1 = 20$
$x_2 = 100$	$x_2 = 100$	$x_2 = 50$
$x_3 = 0.045 * s_1$	$x_3 = 0.045 * s_1$	$x_3 = 0.0045 * s_1$
$x_4 = 0.4 * (x_1 + s_2)$	$x_4 = 0.4 * (x, + s_2)$	$x_4 = 0.4 * (x_1 + s_2)$
$x_5 = 0.7 « s,$	$x_5 = 0.7 * s,$	$x_5 = 0.7 * s_3$
$x_6 = 0.8 * x_4$	$x_6 = 0.8 * x_4$	$x_6 = 0.8 * x_4$
$x_8 = - 0.2 * s_2$		
(* balancing formulas *)		
$x_1 + x_3 - x_4 = 0$	$x_1 + x, - x_4 = 0$	$x_1 \text{ T } x_3 - x_4 = 0$
$x_2 + x_5 - x_3 - x, = 0$	$x_2 + x_5 - x_3 = 0$	$x_2 + x_5 - x_3 = 0$
$x_4 - x_5 - x_6 = o$	$x_4 - x_5 - x_6 = 0$	$x_4 - x_5 - x_6 = 0$
(* solutions *)		
system's sources	system's sources	system's sources
$x_1 = 20$	$x_1 = 20$	$x_1 = 20$
$x_2 = 100$	$x_2 = 100$	$x_2 = 50$
internal flows	internal flows	internal flows
$x_3 = 180$	$x_3 = 130$	$x_3 = 68$
$x_4 = 420$	$x_4 = 150$	$x_4 = 88$
$x_5 = 80$	$x_5 = 30$	$x_5 = 18$
x, = -220		
internal stocks	internal stocks	internal stocks
$s_1 = 4000$	$s_1 = 2889$	$s_1 = 15111$
$s_2 = 1050$	$s_2 = 355$	$s_2 = 199$
$s_3 = 114$	$s, = 43$	$s_3 = 25$
system's sink	system's sink	system's sink
$x_6 = 340$	$x_6 = 120$	$x_6 = 70$

3.5 Dynamic modelling

The term dynamic modelling, as opposed to static modelling, is used here to mean "including time aspects as a of the model". Not only the end state, but also the road towards it and the time involved to get there can be the outcome of such modelling. In this case, information is needed on both stocks and flows in the starting year, as well as information on the (possibly) time-dependent relations between the system's stocks and flows. In practice, such dynamic models have been applied to very limited systems only, mostly because of the extensive data demand. A dynamic model can also be described as a matrix equation, again provided the equations are linear. In this case, the flows and stocks in a certain year $(n+1)$ could then be described in terms of the flows and stocks of the previous year (n). In terms of our example:

$$
\begin{aligned}
x_{1,n+1} &= x_{1,n} = 20 \\
x_{2,n+1} &= x_{2,n} = 100 \\
x_{3,n+1} &= 0.045 \times s_{1,n} \\
x_{4,n+1} &= 0.4 \times (x_{1,n+1} + s_{2,n}) = 0.4 \times (x_{1,n} + s_{2,n}) \\
x_{5,n+1} &= 0.7 \times s_{3,n} \\
x_{6,n+1} &= 0.8 \times x_{4,n+1} = 0.8 \times (0.4 \times (x_{1,n+1} + s_{2,n}) = 0.32 \times (x_{1,n} + s_{2,n})
\end{aligned}
$$

and instead of the balancing formulae we now obtain:

$$
\begin{aligned}
s_{1,n+1} &= s_{1,n} + x_{2,n+1} + x_{5,n+1} - x_{3,n+1} = \\
&= s_{1,n} + x_{2,n} + 0.7 \times s_{3,n} - 0.045 \times s_{1,n} = \\
&= 0.955 \text{ x } s_{1,n} + x_{2,n} + 0.7 \text{ x } s_{3,n} \\
s_{2,n+1} &= s_{2,n} + x_{1,n+1} + x_{3,n+1} - x_{4,n+1} = \\
&= s_{2,n} + x_{1,n} + 0.045 \times s_{1,n} - 0.4 \times (x_{1,n} + s_{2,n}) = \\
&= 0.6 \text{ x } (x_{1,n} + s_{2,n}) + 0.045 \text{ x } s_{1,n} \\
s_{3,n+1} &= s_{3,n} + x_{4,n+1} - x_{5,n+1} - x_{6,n+1} = \\
&= s_{3,n} + 0.4 \text{ x } (x_{1,n} + s_{2,n}) - 0.7 \text{ x } s_{3,n} - 0.32 \text{ x } (x_{1,n} + s_{2,n}) = \\
&= 0.3 \text{ x } s_{3,n} + 0.08 \text{ x } (x_{1,n} + s_{2,n})
\end{aligned}
$$

The matrix equation is then as follows:

$$\begin{pmatrix} \mathbf{1} & 0 & 0 & 0 & 0 & 0 & \mathbf{0} & 0 & 0 \\ \mathbf{0} & 1 & 0 & 0 & 0 & 0 & \mathbf{0} & 0 & 0 \\ \mathbf{0} & 0 & 0 & 0 & 0 & 0 & \mathbf{0.045} & 0 & 0 \\ \mathbf{0.4} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 0.4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.7 \\ 0.32 & 0 & 0 & 0 & 0 & 0 & 0 & 0.32 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0.955 & 0 & 0.7 \\ 0.6 & 0 & 0 & 0 & 0 & 0 & 0.045 & 0.6 & 0 \\ 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.3 \end{pmatrix} * \begin{pmatrix} x_{1,n} \\ x_{2,n} \\ x_{3,n} \\ x_{4,n} \\ x_{5,n} \\ x_{6,n} \\ s_{1,n} \\ s_{2,n} \\ s_{3,n} \end{pmatrix} = \begin{pmatrix} x_{1,n+1} \\ x_{2,n+1} \\ x_{3,n+1} \\ x_{4,n+1} \\ x_{5,n+1} \\ x_{6,n+1} \\ s_{1,n+1} \\ s_{2,n+1} \\ s_{3,n+1} \end{pmatrix}$$

or more compactly:

$$\mathbf{A} \cdot \mathbf{x}_n = \mathbf{x}_{n+1}$$

This means that in order to obtain a result for the year $n+1$, we need to know the magnitude of the stocks and flows in the year n as well as the interannual relations expressed in the coefficient matrix A. For the year $n+j$, the situation can be calculated by raising the matrix to the j-th power:

$$\mathbf{A}^j \cdot \mathbf{x}_n = \mathbf{x}_{n+j}$$

Table 3.2 shows the results of the calculations for several years.

Table 3.2 Results of calculations with the dynamic set of equations for several years, starting from the 1990 situation

year n: 1990	year n+1	year n+2	year n+10	year n+50	year e»
		(* system's sources *)			
x_1 = 20	x_1 = 20	x_1 = 20	x_1 = 20	x_1 = 20	x_1 = 20
x_2 = 100	x_2 = 100	x_2 = 100	x_2 = 100	x_2 = 100	x_2 = 100
		(* internal flows *)			
x_3 = 180	x_3 = 180	x_3 = 179.99	x_3 = 172.16	x_3 = 140.32	x_3 = 130
x_4 = 420	x_4 = 428	x_4 = 336.8	x_4 = 197.8	x_4 = 161.29	x_4 = 150
x_5 = 80	x_5 = 79.8	x_5 = 83.86	x_5 = 40.52	x_5 = 32.46	x_5 = 30
		(* internal stocks *)			
s_1 = 4000	s_1 = 3999.8	s_1 = 4003.7	s, = 3794.1	s_1 = 3110.2	s_1 = 2889
s_2 = 1050	s_2 = 822	s_2 = 685.2	s_2 = 486.9	s_2 = 382.3	s_2 = 355
s_3 = 114	s_3 = 119.8	s_3 = 103.3	s_3 = 56.9	s_3 = 46.1	s_3 = 43
		(* system's sink *)			
x_6 = 340	x_6 = 342.4	x_6 = 269.44	x_6 = 158.24	x_6 = 129.03	x_6 = 120
		(* stock changes over the year *)			
s_1: 0	- 0.2	+ 3.9	- 31.6	- 7.9	0
s_2: - 220	- 228	- 136.8	- 5.6	- 1.0	0
s_3: 0	+ 5.8	- 16.5	- 1.0	-0.1	0
total: -220	- 222.6	- 149.4	- 38.2	- 9.0	0

From Table 3.2 it can be seen that the stock changes are large at first, but will decrease over the years. Ultimately, stocks and flows will tend toward an equilibrium situation. This situation is identical to the steady end state calculated by the static model, and is independent from the starting situation in year *n*. By calculating A" this can be proven:

$$A^{\infty} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.045 & 0 & 0 \\ 0.4 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.7 \\ 0.32 & 0 & 0 & 0 & 0 & 0 & 0.32 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0.955 & 0 & 0.7 \\ 0.6 & 0 & 0 & 0 & 0 & 0.045 & 0.6 & 0 \\ 0.08 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.3 \end{pmatrix}^{\infty} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.24 & 1.24 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.25 & 1.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.25 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5.32 & 27.54 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2.11 & 3.11 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.36 & 0.36 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

As we can see, all columns except the two leftmost are reduced to zero. This means that the end situation is calculated *only* from the system's fixed inflows, and is therefore independent of any starting situation. Moreover, we have by this action duplicated the origins analysis as described in

Section 3.4, by expressing every flow and stock in terms of the system's sources.

With a dynamic model, calculations can be made on measure packages with respect not only to their "intrinsic" effectiveness, but also to their expected effects for a specific year in the future, and the time it takes for a measure to become effective. Other time-dependent factors, such as population growth, can be introduced as well. A dynamic model is therefore the most suitable for scenario analysis, provided the required data are available or can be estimated with adequate accuracy. And this is of course the major problem, since the data requirement is much larger than in the case of static modelling, and moreover far more accuracy is expected of a scenario analysis in which future situations are predicted. Another difficulty lies in the fact that in a dynamic system an equilibrium situation does not necessarily exist. The dropping of the equilibrium requirement in the model means the loss of an important check on the results of the calculations, which must be replaced by an even more careful check of the input data beforehand.

As far as we are aware, no operational general substance flow model based on the aforementioned principles exists at present, although some are in progress (Bader, 1993) and others are in planning (Udo de Haes et al., 1992). Dynamic substance flow models, or rather models including dynamic aspects, do exist for smaller systems. Various models for a of the agro-ecological system may be mentioned here (Kroes, 1988) as well as atmospheric models related to global climatological processes (Houghton et al., 1991). For the societal flows, a dynamic model by Gilbert et al. (1992) may be mentioned as an example, describing cadmium flows especially related to batteries.

In several cases, dynamic modelling is simulated by a shrewd application of a static model. Sometimes, multiplication factors are introduced to obtain an idea of the situation in a year in the future compared to the present: for example, an expected population growth of 5% from 1990 until the year 2015 is translated into a multiplication factor of 1.05 for all flows directly connected to population size. This procedure is followed, for example, by the Dutch National Institute of Public Health and Environmental Protection (1994) for estimating the environmental consequences of various economic scenarios. In cases of delayed impacts (for example, discarding of durable products or mobilizing of metals in soils) this will lead to less than accurate outcomes. In other cases, dynamism is simulated by application of a static model to calculate chronological series. The year 1 model is modified to suit year 2, and so on. This procedure is correct, if somewhat elaborate, and has the advantage of providing an opportunity to introduce modifications at any desired point in time. The well-known RAINS model for acidification (Alcamo et al., 1990) is an example of such an approach, as is shown by Anderberg et al. (1993).

3.6 Conclusions and discussion

The modelling of the system's substance flows and stocks can be attempted in different ways. Three are identified here:

- bookkeeping: keeping track of flows and stocks afterwards by registering them, thus enabling policy makers to spot trends, and to evaluate the effects of certain changes including policy measures;
- static modelling: specifying the relations between stocks and flows, thereby enabling policy makers to trace the origins of pollution problems on the one hand, and estimating the effectiveness of measures on the other;
- dynamic modelling: including time as a modelling parameter, thereby making it possible to predict future situations.

There is no "best" choice: each type of modelling is useful, each has different functions for

supporting environmental policy, and each has different data demands and different requirements for the exactness of the outcome. This last point is especially relevant for the choice for static or dynamic modelling: with dynamic modelling, the outcome would be a prediction of the future, which must be more or less accurate in order to be able to serve as a basis for policy decisions; with comparative static modelling, the outcome would be an indication of the general usefulness of certain measures *compared to others,* not pretending to predict and therefore obviously excluding many uncertainties.

The computer tool SFINX can be used as a bookkeeping system and as a static model. As such, it has been applied in various case studies regarding heavy metals, nutrients and organic chlorine compounds. Specific applications, a from generating the overview of flows and stocks, are the origins analysis, wherein specific problematical flows are related to their societal causes, and the calculation of the effectiveness of policy measures on a comparative static basis.

This article does not elaborate much on the data side of the analysis. Which data are needed, dependent on the choice for the type of modelling, is specified in general terms. The need for a general database, containing standardized data on flows and stocks on the one hand and on economic and environmental processes on the other, is not treated here but would be very useful to discuss. How robust the results of an SFA are in view of missing data or wide margins of error, and how this could be tested, is another very relevant issue. A procedure for such a sensitivity analysis could be a subject for further investigation. This is treated in more detail in Chapter 9 and Appendices 2 and 3. Another issue is the generation of the distribution coefficients out of the "bookkeeping" overview and other sources. This involves the choice of the fixed variables, the meaning of the coefficients, the possibilities to introduce economically determined coefficients next to coefficients of a more technical nature, and many other details. There are different procedures by which this can be done, each leading to different outcomes when regime changes are introduced. The Input-Output Analysis procedure on the one hand is rigidly determined. With SFINX on the other hand, it is completely open: the user has the freedom to introduce any additional knowledge with regard to the processes for determining the coefficients. This makes SFINX more flexible, but asks much more from the user. Here, too, a general discussion on how to approach this issue could be very useful.

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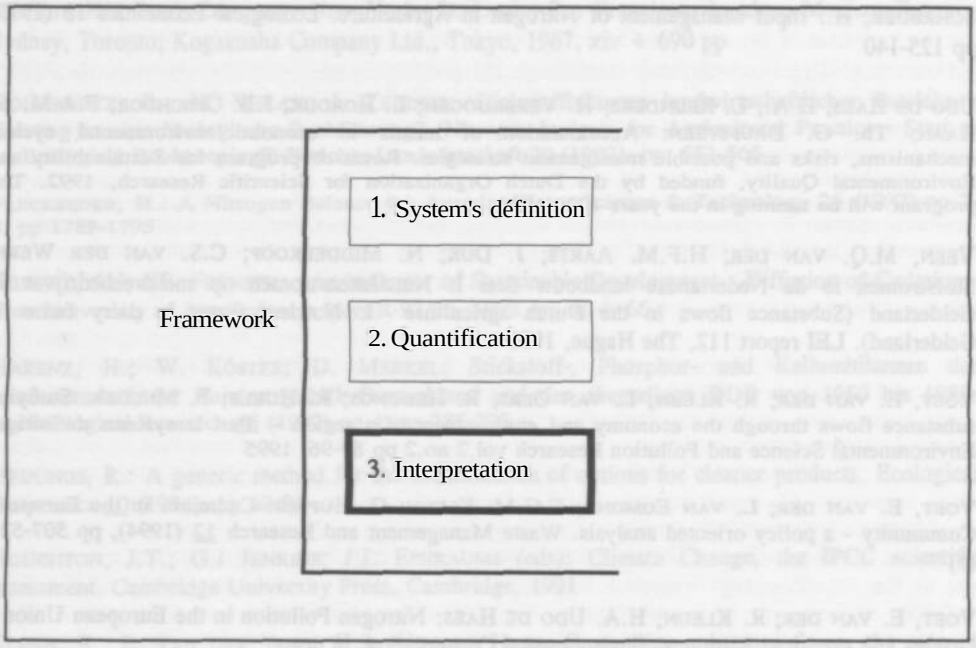
1. System's définition
Framework
2. Quantification
3. Interpretation

CHAPTER 4 INTERPRETATION OF THE RESULTS

4.1 Introduction

In Chapters 2 and 3, the first and second component of the general SFA framework - the system's definition and the quantification of the overview of flows and stocks - have been treated. In this chapter, the subject is the third component: the interpretation of the SFA results. By "the results", the quantified overview of flows and stocks of a substance in a region is meant. This overview can be used to draw conclusions with regard to a region's substance management regime. The question to be answered in this chapter is: how can the overview of flows and stocks be translated into directly policy relevant information?

Policy relevant information in this case refers to substance policy. Four categories can be distinguished:

1. Depletion of geological/environmental stocks
2. Pollution
3. Management of economic stocks and flows
4. Problem shifting.

Some conclusions can be drawn directly from the overview, or after a brief selection or summary procedure. However, whether or not these flows and stocks are in any way problematical, does not follow directly from the overview. To obtain an impression of this, additional information is required. Section 4.2 deals with evaluating flows and stocks directly from the overview.
In Section 4.3, the evaluation of pollution problems is treated. For this, additional information is required with regard to the harmful nature of the substances.
In Section 4.4, the subject is the formulation of indicators for integrated substance chain management. Indicators are formulated in all four categories, but especially with regard to the management of economic flows and stocks and the problem shifting mechanisms.
In Section 4.5, finally, a general set of information, that can be derived from the overview of flows and stocks, is proposed regarding all four categories. This set should provide the main information for a substance policy, within the limits of the SFA tool.

4.2 The direct use of the SFA overview

The overview of flows and stocks contains a great deal of information, which makes it difficult to precisely extract the desired information from it.

A first possibility is to summarize the overview into a brief characterization of the substance regime. Two different summaries are discussed below: the substance flow diagram, and the substance's economic life cycle.

The Substance Flow Diagram (SFD)

In Chapter 2 (Figure 2.1), the SFD is presented as a possible summary of the SFA overview. This specific summary dates from when the SFA method was in its first stages of development (Udo de Haes et al., 1988). It was then used as an information tool in order to introduce a substance deposit system (Huppes, 1993), where border control of substances was essential. The information that can be obtained from it therefore is border information: various categories of inflow and outflow, and moreover a view of economy and environment in comparable terms. This opens possibilities for an evaluation on a very generalized level. The absolute and relative magnitude of the system's sources, the emissions, the accumulations, and the amount disappearing from the system through degradation or immobilization become apparent at first glance. The same is true for the magnitude of the economic flows compared to the environmental ones.

The substance's economic life cycle

Another type of summary, with more attention to the economic processes, was developed (see Chapter 2, Figure 2.2): the summary of the substance's economic life cycle. From this summary, the magnitude of the economic cycle, the losses from the economic cycle in the various life cycle stages (both absolute and relative), the amount of re-use and recycling within the system, and the amount contributed as a result of imports and exports ("openness" of the economy, or degree of self-sufficiency) can be seen. This may provide some information, although very general, with regard to the possibilities for a further technical "closing of the chain" by recycling and by measures directly addressing emissions, as opposed to the need for a volume policy.

Possibilities to evaluate the overview of flows and stocks directly, without additional information and without further calculations, are therefore limited but nonetheless important. A summary of a region's overall substance regime offers some first rough recommendations for environmental policy.

4.3 Evaluating environmental consequences of material's regimes

This section is concerned with the possibilities for evaluating the environmental consequences of a certain substance regime. This is useful for either confronting flows or stocks with a target level of some sort, or for bringing the outcomes of SFA studies for different substances under comparable terms. Pollution problems can be distinguished from depletion problems.

For depletion problems, the economic inflow of virgin material is the relevant flow. The "target level" for this, from a depletion point of view, generally is the zero level: less is better. From the SFA point of view, the resources we are referring to are generally elementary geological resources. Although such resources cannot be depleted in an absolute sense, they can become technically unavailable once dissipated into the environment, and we can still speak of a depletion problem. For non-geological resources such as nitrogen, depletion may not exist as a problem. Finding a measure for such a problem is in such cases useless.
The evaluation of depletion problems will not be discussed further in this section.

For an evaluation of pollution problems, information is required with regard to the environmental harmfulness of the substance. Two possibilities are discussed in this section:
1. the use of environmental standards
2. the use of problem contribution equivalency factors.

Ad 1. The use of environmental standards
By introducing environmental standards, it becomes possible to relate flows and stocks to a desirable, sustainable, or otherwise acceptable level, and thereby to judge them in an absolute sense. However, environmental standards generally do not refer to flows or stocks directly, but to concentrations or exposures. A direct confrontation is possible, for example, in the case of emission or deposition targets, where the acceptable level is expressed in flow terms. But this is an exception rather than a rule. In most cases, therefore, a translation must be made. The procedure for such a translation is described below.

The first step is to select the relevant flows out of the SFA overview, derived from known problems related to the substance in question.
The second step then is to ascertain whether there are some directly flow-related standards, policy targets or no-effect levels. For nitrogen, for example, this happened to be the case for the anthropogenic inflow into the North Sea: a reduction target of 50% was adopted by the International North Sea Conference (INSC) relative to 1985, which means that half the 1985 level could be used as the "acceptable level" (see Chapter 8).
If no flow-related targets exist, there is a choice of two possibilities: either the existing standards or target levels must be translated into flow related terms, or the flows out of the overview must be translated into the terms of the standards. It depends which route is most suitable. Referring to the nitrogen example again, the first possibility was chosen for the atmospheric deposition, since the second one was not possible. The second possibility, translating flows and 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 human being) that the flow or stock is distributed over. This approach has been taken, for example, in the cadmium case study for agricultural soil: the yearly accumulation was translated into a concentration increase of 4.5 μg Cd/kg soil per year (see Chapter 7). Data on the soil stock can be translated likewise into a concentration already present in the soil.

The introduction 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), applied in the USES evaluation system for substances (Jager & Visser (eds), 1994). The PEC, a long term equilibrium 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-limit, or another acceptable concentration level.

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.

Ad 2. The use of equivalency factors

In some cases, the above mentioned approach is not possible, or is too elaborate. This can be illustrated by the case of chlorine compounds (Kleijn et al., 1993; Tukker et al., 1994), in which there were two problems. In the first place, there were some 100 different compounds, strongly connected within the economic system, included in the analysis. It was impossible to trace the environmental fate of all of those; therefore, an evaluation on the emission level was preferred. In the second place, the potential environmental impacts of these compounds vary widely, which means that it was not possible to find one term to express them that would cover all relevant aspects. The analysis of the economic flows was performed in kg Cl in order to be able to draw mass balances, but kg Cl does not provide adequate information regarding environmental risks if Cl could refer to chloride, dioxins, CFCs, or PVC. Therefore, the emissions of the various chlorine compounds were translated into problem contribution equivalency factors, borrowed from the product LCA impact assessment (Heijungs et al., 1992). These factors refer to specific environmental problems, such as global warming, ozone layer depletion, toxicity, etc. Every emission was translated into four (Kleijn et al., 1993) or eight (Tukker et al., 1994) values, thus reducing hundreds of separate emissions into 4 or 8 totals respectively. Changes in regime thus are translated into changes in the problem-causing potential of the total chlorine chain. Within the chlorine chain, the contribution of the various sub-chains, separate processes or process clusters, or compounds specific to the problem potentials can be identified. This approach clearly has some limitations: by translating emissions into problem contribution potentials, information with regard to space and time is lost. No comments can be made on whether some emission will actually lead to a transgression of concentration limits in a specific region. Thus, the analysis is purely comparative and not absolute. In the case of chlorine, the advantages of being able to analyze the chain as a whole clearly outweigh the unavoidable concurrent information loss.

This approach can also be taken with regard to other compounds. In a case study on six heavy metals in the Netherlands (Annema et al., 1995), the inflow into the agricultural soil was multiplied by its human and eco-toxicity equivalency factor from the LCA impact assessment list[1]. Figure 4.1 shows the results. This led to the somewhat surprising conclusion that the top scorer for ecotoxicity is zinc by a large margin, followed by copper. For human toxicity the

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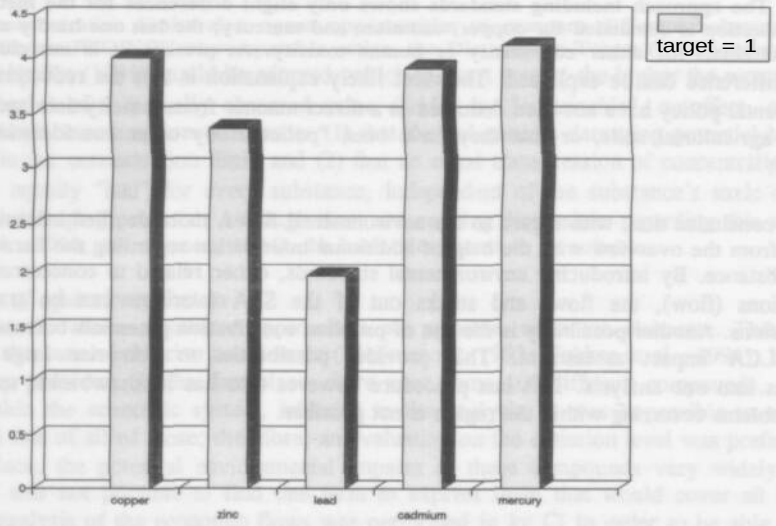
[1] The equivalency factors out of the LCA guide (Heijungs et al., 1992) contain an element regarding the toxicity of the substance and a somewhat crude and incomplete element of the environmental fate. Currently, there are ongoing discussions on how to improve this *fate* element in the equivalency factors for toxicity.

highest score, as might be expected, is due to cadmium. In this case, the approach of confronting flows with environmental standards is preferable, since the same object is served with no information loss regarding space and time, and a relative as well as an absolute evaluation is possible. The results of both approaches should point in the same direction, provided the environmental standards are derived from the hazardous qualities of the substances. However, if we compare the two approaches for the group of six (see Figure 4.1), this does not appear to be the case. The approach including standards shows only slight differences for the metals, and the largest reduction is demanded for copper, cadmium and mercury; the last one hardly scoring at all on the potentials for either ecotoxicity or human toxicity. At present, it is not clear how this marked difference can be explained. The most likely explanation is that the reduction targets for environmental policy have not been deducted in a direct manner from toxicity data and the current flows to agricultural soils, or that they have been "polluted" by other considerations, such as feasibility.

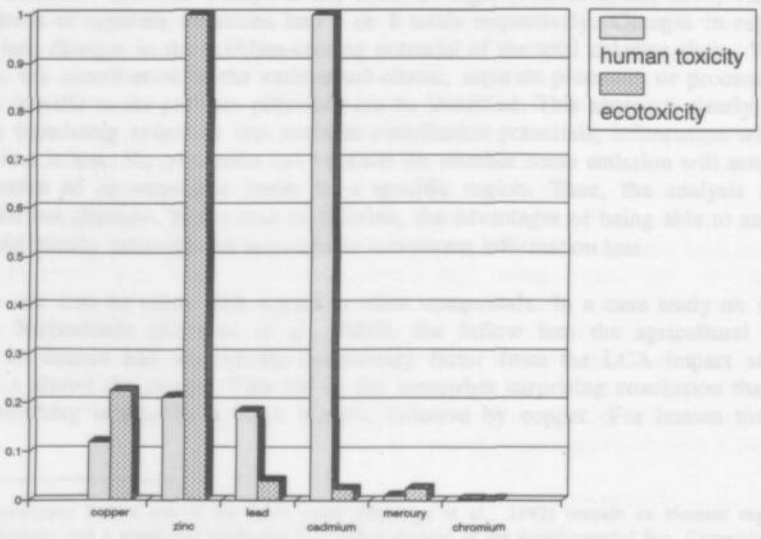
It can be concluded that, with regard to the environmental flows, more detailed information can be obtained from the overview with the help of additional information regarding the harmful qualities of the substance. By introducing environmental standards, either related to concentrations (stock) or emissions (flow), the flows and stocks out of the SFA overview can be translated into transgressions. Another possibility is the use of problem contribution potentials borrowed from the product LCA impact assessment. This provides possibilities to comprise large groups of substances into one analysis. This last procedure however also has its drawbacks: specifying the actual problems occurring within the region is not possible.

Figure 4.1 Evaluation of environmental flows by confrontation with policy targets (4.1a) or with LCA equivalency factors (4.1b)

4. la Transgression of policy targets for the input of five metals in agricultural soils in The Netherlands in 1990. Actual input divided by target input. From: Annema et al., 1995.



4.1b Relative toxic potential of the accumulation of six metals in agricultural soils in The Netherlands in 1990. For human toxicity and ecotoxicity, relative to the highest score, which is set to 1. From: Annema et al., 1995; Heijungs et al., 1992.



4.4 Indicators for integrated chain management

4.4.1 Introduction

In 4.3, possibilities for evaluating the environmental flows with the help of environmental standards have been described. For the economic substance flows, however, no such approach is possible. There are no standards, nor can they be imagined, since flows and stocks do not cause any problems as long as they are locked within the economic system. However, it would certainly be useful to be able to comment on the economic substance flows as well, as the instigators for the environmental flows. This could then serve either as an early warning, or as a recommendation for environmental policy. After all, in order to solve the environmental problems, it is the economic flows that must be influenced. In this section, the definition of indicators for an integrated substance chain management as a part of the "interpretation" step of the SFA framework is the subject. Extra attention is given to the economic substance flows.

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 of "indicator" is not strictly defined, and in practice many widely different things may serve as indicators. A general demand made of indicators seems to be that they are easier to measure than the things they indicate. Other general requirements concern their possibility to be used for monitoring the success of environmental policy, their ability to be understood by non-scientists, and their appealing qualities.

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, 1993a). 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. The classification made by Bakkes et al. (1994) closely corresponds to the OECD classification, but explicit attention is demanded in addition for problem-shifting to other regions.

In some sources, a difference is made between indicators and indices: an indicator is a single parameter variable, that is indicative of other variables as well, while an index is constructed out of more than one variable (OECD, 1993b). Opschoor & Reijnders (1991) speak of selections ("typical" or "representative" variables) vs. aggregates (transformations of underlying variables), corresponding roughly with the "indicator" vs "index" classification.

The indicators in this chapter 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:

- a measure for 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.

An important issue is the choice for reference values. The information can be interpreted better if the actual state of the flows and stocks is in some way be related to a desirable or "sustainable" state. In some cases, especially with regard to the environmental flows, references can be distilled out of environmental policy plans and comparable sources. Often, however, such references are lacking. In such cases, reference values must be defined together with the indicator, although this will not always be possible.

In this chapter, the distinction between simple and elaborate indicators is made in the following terms:

- selection indicators (choosing one (group of) flow(s)/stock(s) as an indicator);
- combination indicators (calculating an indicator from several flows and/or stocks).

Indicators of the selection type generally can be defined and appointed without problems. The difficulties lie in the interpretation: what is the indicative value of this specific flow or stock, and how can environmental policy make use of it? For combination indicators, the calculating procedure is the most difficult step, because often there is a good idea beforehand of what the indicator ought to express. This will be shown in more detail in the coming sections.

Three types of indicators, that can be extracted from the overview of flows and stocks, will be treated in this section. They are discussed in order of "upchain distance" from the pollution problems we are concerned with:

1. environmental indicators, providing information regarding the state of the environmental flows and stocks and possible changes therein, in § 4.4.2;
2. economic indicators, doing the same for the economic flows and stocks, in § 4.4.3;
3. system indicators, providing information regarding the system as a whole, in § 4.4.4.

Environmental indicators can selected environmental flows, stocks or accumulations or combinations thereof. Emissions and extractions can be regarded as environmental indicators as well, but may also be viewed as belonging to the economy on account of the forces that cause them. Here, the choice is made to classify these interactions under the economic indicators, and related to the economic substance management regime rather than to the environmental carrying capacity. System indicators can be directed either at economy and environment together (for example, the total accumulation in the system), or at a comparison between economic and environmental flows.

In this section, various specific indicators will be discussed with regard to their definition, their indicative value, the procedures employed to calculate them, and the interpretation of them for environmental policy. Together, they cover different aspects of the substance's life cycle. If only one indicator, with a limited scope, is used, it can lead to irrelevant or even wrong conclusions. For example, an indicator for problem-shifting to the future could possibly present an outcome that is opposite to that indicated by an indicator for the present situation: less emissions now may cause more in the future. It is likely, in view of the different characteristics of substances, that "a complete set" would look different for every type of substance. The definition of a more or less complete set of indicators for evaluating a substance management regime is the subject of Section 4.5. This complete set also contains some indicators not discussed in Section 4.4, such as the emissions (aggregate or detailed) from the economy to the environment, or the *per capita* resource consumption. Section 4.4 is limited to the discussion of several relatively new or partly new indicators developed especially for the evaluation of substance chains within the framework of SFA.

The indicators presented in the following sections will be discussed according to the following

procedure:
- short introduction
- the significance of the indicator
- method of calculation
- interpretation for environmental policy.

4.4.2 Environmental indicators

The environmental indicators have a relatively close relationship to the pollution problems that they indicate, and therefore hover on the border between *state* and *pressure* indicators. After a short introduction, two specific indicators are discussed as examples, worked out in different case studies: environmental accumulation, and a measure for the eutrophication problem.

The selection of single flows or stocks often provides very useful environmental indicators. The procedure in this case is very simple: one specific flow or stock out of the overview is selected as an indicator. Which specific flows or stocks should be selected depends on the substance under study and the environmental problems connected with it. The main criterion for selecting specific flows or stocks is that they are clearly related to one or more environmental problems. The environmental accumulation discussed below is such a *selection* indicator. An example of an indicator generated by combining flows and/or stocks is the eutrophication indicator for the Netherlands, starting from the concept of "surplus". As will be made clear, it is a matter of careful consideration to determine how exactly to define such indicators, because different starting points lead to different outcomes.

Indicator 1: Environmental Accumulation

Environmental accumulation is, although neither stock nor flow, in principle a *selection* indicator. The increase of a certain stock over the year is selected as the relevant indicator. It can be defined either on an aggregate (total environmental accumulation) or on a detailed (accumulation in one specific stock) level. It may be expanded into a combination indicator (accumulation compared to stock magnitude, accumulation compared to the nodes throughput).

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 maybe 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:

As a first 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 current concentration of the substance. This approach has been taken in the cadmium case study for agricultural soil, as described in Chapter 7: the accumulation was translated into a concentration increase of 4.5 μg/kg per year. From a completely clean situation, this would mean a period of almost two centuries before the Dutch 0.8 mg/kg limit (Zoetemeijer, 1994) would be transgressed. Since the cadmium soil stock is already considerable, the time will be much shorter, depending on the local situation.

A second 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. However true this may be, this option does not do justice to the sometimes difficult to trace mechanism of "closed loop accumulation": the slow process of poisoning that occurs in cyclic processes (both economic and environmental) when a small yearly input is added to a large basic closed cycle. Because the yearly accumulation in such a case is small, it can easily be ignored. Nevertheless it may lead to a rise in concentration above the limit in due time. Whereas the curve (yearly accumulation against time) may level off quickly for some larger accumulation, it may continue to rise for a long time in cases of small accumulations.

A third possibility is to calculate the long-term 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.

A hypothetical (because no stock data are available, and the average concentration is a wild guess) analysis of cadmium in the EU would look like the following: consider the current average cadmium concentration in the top 10 cm of the agricultural soil to be 0.5 mg/kg. This would mean a total stock of roughly 1500 tonnes of cadmium in agricultural soil. Calculations with SFINX show that in the long-term steady state situation of the 1987 regime, the accumulation will have resulted in an equilibrium stock of 3800 tonnes. This would mean an average concentration of 1.3 mg/kg, and therefore a transgression of the 0.8 mg/kg limit. The accumulation of 1987

therefore can be considered unacceptable, and is indeed an indicator of future problems.

Indicator 2: Mineral Surplus, an indicator for the eutrophication problem.

The eutrophication indicator has been developed for the RMNO (Van der Voet, 1992). Criteria were developed for measuring and judging a number of environmental problems occurring in or contributed to by the Netherlands. For the problem of the eutrophication ("vermesting", overfertilizing) of the environment an indicator was developed based on the concept of mineral surplus. It is a combination indicator, defined at a rather aggregated level.

The significance of the indicator

The mineral surplus indicator is defined in two different ways: (1) indication of the risk for the occurrence of environmental problems related to minerals, i.e. eutrophication problems, within the system, and (2) indication of the risk for eutrophication problems occurring anywhere, inside and outside the system, as a result of the mineral management of the system.

Method of calculation

The concept of "surplus" is defined in two ways as well, both related to the Substance Flow Diagram described in section 4.2.2 and Chapter 2. A eutrophication problem within the system occurs when the inflow into the environment exceeds the outflow. The environmental inflow consists, in terms of the SFD, of the transboundary inflow, the natural formation or erosion, and the emissions from the economic system. The outflow is the transboundary outflow, the degradation or immobilization, and the extraction of minerals from the environment. In this definition, *the surplus equals the system's total environmental accumulation:* IN - OUT for the environmental subsystem, and the indicator is identical to Indicator 1, the environmental accumulation, on an aggregate level.

This approach is consistent when we are considering the risk for eutrophication problems occurring within the system. However, the shifting of problems to other systems, caused by the transboundary outflow of nutrients, is not taken into account. The larger the outflow, the lower the surplus but at the same time the heavier the problem-shifting to other areas. A second definition of surplus, to be used in addition to the one given above, may solve this problem. This is a definition of the *mineral surplus that is generated by the system,* regardless of where this surplus ends up. This is calculated again by IN - OUT for the environmental subsystem, considering this time only the natural formation or erosion and the emissions from the economic systems as IN, and the degradation or immobilization and the extraction as OUT. The transboundary inflow and outflow are thus left out. By comparing the surplus that is generated by the system (i.e., the surplus according to definition 2) to the environmental accumulation (i.e., the surplus according to definition 1), a picture is obtained of the system functioning as a minerals sink or a minerals source for other systems.

Interpretation for environmental policy

The choice for either one of the definitions for "surplus" depends, of course, on the information specifically required while formulating a minerals management policy. It will probably be best to consider both. In the RMNO report, two minerals are taken into consideration: phosphorus (P) and nitrogen (N). The same calculation procedure applies for N and P. However, different reference values can be defined for them in view of the environmental consequences of a surplus being different. Whereas for P the reference value should be zero, for N it could be an "allowable surplus", which must be defined specifically for each region. As always, it is easier to use the indicator to compare than to judge absolutely: when different years or different scenarios are

compared, the one with the lowest surplus may be regarded as the most desirable.

4.4.3 Economic indicators

In analogy to the environmental indicators, economic indicators are used to identify the state of the societal flows and stocks of substances. These indicators ultimately derive their meaning from the environmental situation: they indicate the state of the economy from the point of view of the extractions from and the losses to the environment, and therefore may be categorized as *pressure* indicators. On the one hand, the relevance of these indicators is indirect. On the other hand, looking so far "upchain" may provide early warnings by estimating the consequences of a substance regime.

A "good" materials regime from an environmental point of view can be defined as a regime that holds the economy/environment interactions to a minimum. This must be expressed in the indicators. Several aspects are relevant for the magnitude of these physical interactions and may be translated into indicators of some sort: the absolute and relative amount of the extractions and emissions themselves, the societal demand or the required use level within the region, and the region's economic throughput. A few examples of already existing indicators in this area must be mentioned: the materials intensity of a national economy (Bringezu, 1993), the MIPS-indicator (Schmidt-Bleek, 1993), consumption of energy and specific materials (pesticides, fertilizer, wood, water,...), recycling of specific products or materials (paper, aluminium, glass,...). Such already existing indicators can be useful for evaluating a substance regime as well. In Section 4.5, when defining a complete set, already defined indicators are also included. This section is focuses on new indicators, or existing ones with a new perspective.

This section begins with a general paragraph on "closing the cycle", wherein the terms are defined for the method of calculation of the economic indicators. After that, six separate indicators are described and partly worked out in an example. As a "selection" indicator, the economic accumulation is put forward in this section. Its characteristics are analogous to the environmental accumulation indicator described in the previous section can be detected here. Most indicators presented in this section belong to the "combination" type. Of these, most are indicators reflecting a very high aggregation level, i.e. they say something about the region's economy as a whole. This is true also for the "selection" indicators, and is different from the indicators on the environmental side. Although one could conceivably define an indicator related to one key flow or process within the economic system, much more digging is required to identify key flows and processes within the economic system. Our knowledge of the economy with regard to the flows and stocks in it and the driving forces behind it is at this moment much more limited than the knowledge of the environmental substance pathways.

"Closing the cycle" as the core issue for indicators regarding the economic substance management regime

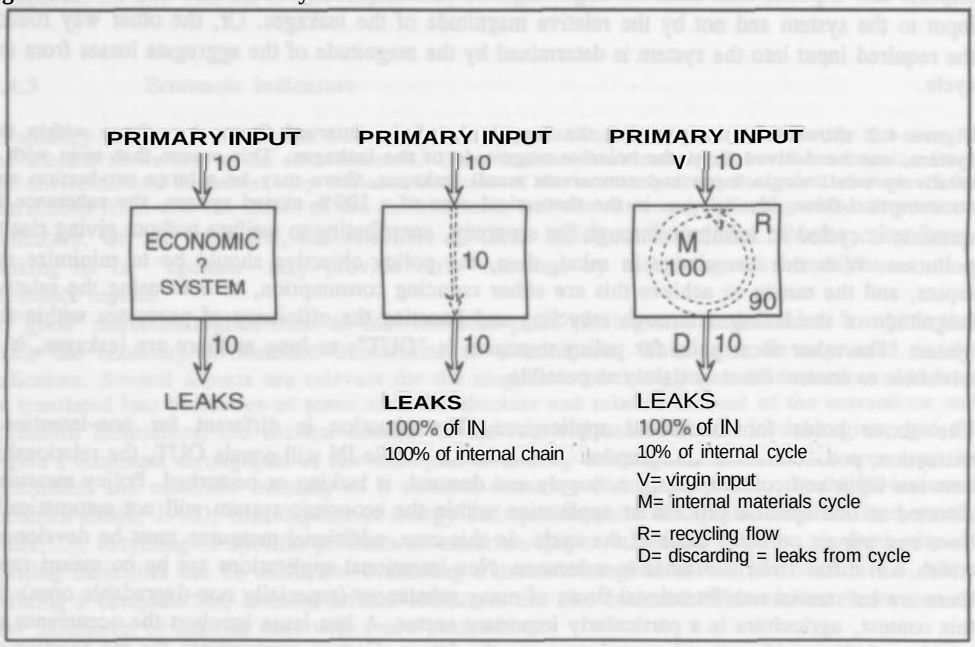
In environmental policy regarding substances, there is often talk of "closing materials cycles" and calculating the "degree of closedness" of materials cycle as an indicator of the soundness of a region's materials management. To operationalize such an easily stated concept provides difficulties, however. Figure 4.2 shows a very simplified picture of an economic substance cycle in which, for simplicity's sake, exchanges with other systems by imports and exports are ignored. Such an economic substance cycle theoretically is 100% closed if it contains no leakages. Given the existence of one or more leakages, regardless of their magnitude, for an equilibrium situation it *always* holds that IN = OUT, in other words the aggregate input (primary materials) must be equal to the aggregate output (leakages), taken over the entire economic system. Deviations from the equilibrium situation in actual regional situations are coincidental: caused by accumulations or

imports and exports. The absolute magnitude of the leakages is thus governed by the aggregate input to the system and not by the relative magnitude of the leakages. Or, the other way round, the required input into the system is determined by the magnitude of the aggregate losses from the cycle.

Figure 4.2 shows that, in contrast, the magnitude of the *internal* flows, i.e. those within the system, can be derived from the *relative* magnitude of the leakages. This means that even with a relatively small virgin input and concurrent small leakages, there may be a large production and consumption flow. Ideally, i.e. in the theoretical case of a 100% closed system, the substance in question is cycled ad infinitum through the economy, contributing to welfare without giving rise to pollution. With this knowledge in mind, then, the policy objective should be to minimize the inputs, and the means to achieve this are either reducing consumption, or decreasing the relative magnitude of the leakages through recycling and boosting the efficiency of processes within the system. The other focal point for policy measures is "OUT": as long as there are leakages, it is advisable to control these as tightly as possible.

The above holds for intentional applications. The situation is different for non-intentional extraction, production and consumption of substances. While IN still equals OUT, the relationship between input and consumption, i.e. supply and demand, is lacking or perturbed. Policy measures directed at one specific process or application within the economic system will not automatically have any impact on other parts of the cycle. In this case, additional measures must be developed, which will differ from substance to substance. Non-intentional applications are by no means rare; there are substantial non-intentional flows of many substances (especially non-degradable ones). In this context, agriculture is a particularly important sector. A last issue involves the occurrence of *problem shifting*, either to other regions or to the future. Certain propositions for the solution of pollution problems could cause those types of problem-shifting.

Figure 4.2 The economic cycle and its losses



The indicators discussed below cover the various aspects that have been introduced above as the relevant ones for evaluating a region's economic substance management, i.e. determining the degree of closedness of the economic substance cycle.

- The substance management regime of the region itself is expressed in Indicators 3 and 4: the primary vs. secondary materials use and the economic efficiency of the life cycle stages.
- The problem of non-intentionality is addressed in indicator 5.
- Indicator 6, economic accumulation, is relevant for problem-shifting to the future.
- For the phenomenon of cleaning up at the expense of other regions, indicator 7, the "pollution export indicator", is defined.

Indicator 3: primary vs. secondary materials flows

Figure 4.2 shows that there is no point in establishing a leakage percentage for the system as a whole in the most obvious manner, i.e. using the quotient total losses/total input, or D/V in terms of Figure 4.2. After all, in the long-term equilibrium situation this will always be 100% (exports excluded). A more useful approach is therefore to calculate overall leakage as a percentage of the internal cycle (M, in Figure 4.2). This can be approximated by calculating the fraction of recycled or secondary resource consumption relative to overall resource consumption. The new, or *virgin input* is then the determining factor for leakage losses, remembering the basic rule IN = OUT. Two ways of approaching this are given, both of the "combination" type:
(1) regarding IN: the contribution of primary materials to the total materials inflow
(2) regarding OUT: the discarding rate of waste materials.

In a steady state situation and without the complicating factor of imports and exports, the two procedures would render an identical outcome, as can be seen from Figure 4.2. In an actual situation, the two will almost certainly be different.

The significance of the indicator

The contribution of the virgin input to the total materials cycle, as well as 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

It is not always easy to obtain the information with regard to the "primary" or "secondary" status of materials from the overview of stocks and flows.

For the first calculation method, the general formula (referring back to Figure 4.2) is: V/M, V being the amount of primary materials used, and M the total internal materials cycle. The main problem is that of the imports: it is generally not known whether imported products are generated from primary or from secondary materials. For the region's environmental policy the relevance of this is limited, since it can hardly be influenced. A certain assumption can be made with regard to the origins of imported products, which will have the nature of an educated guess.

For the second calculation method, the general formula is D/M, with D the total amount of discarded materials. The main difficulty here is the economic accumulation. 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 end situation belonging to the substance's economic regime (see Chapter 3) 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 may be quite adequate. The general formula then becomes 1 - (R/M).

For the flows of copper in the Netherlands, an example of both calculating procedures is shown. They refer only to the intentional Cu applications. Thus, copper as an additive in fodder is included, copper in manure is not.

1. Relative contribution of primary materials to the total materials cycle.

In the Netherlands, the copper industry imported 123,111 tonnes of copper in 1990. For the contribution of primary materials, the world ratio was taken: 82.5% primary and 17.5% secondary (Van Tuinen, 1993; US Department of the Interior Bureau of Mines, 1993; UNCTAD, 1990). Moreover, 25,928 tonnes of copper entered this industry as collected scrap: 100% secondary. Other economic inputs consist of a total of 10,878 tonnes Cu in imported products. For these products, the global ratio was taken once again.

This would lead to the following calculations:

total primary:	123,111 * 0.825 + 10,878 * 0.825 = 110,541 tonnes Cu (69%)
total secondary:	123,111 * 0.175 + 25,928 + 0.175 * 10,878 = 49,376 tonnes Cu (31%)
TOTAL	100,541 + 49,376 = 159,917 tonnes Cu (100%)

The virgin input, or "leakage", thus is 69%.

2. Relative disposal of the total of (waste) materials.

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 below. The figures refer to the steady state situation belonging to the 1990 copper regime of The Netherlands.

Table 4.1 Recycling of discarded copper products, The Netherlands' 1990 regime, steady state situation.

application	Cu use flow (tonnes, 1990)	recycling % %	recycling flow (tonnes)
consumers 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%	•
food	726	0%	'
TOTAL	72,907	64%	46,904.

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

Interpretation for environmental policy

The virgin input, as stated above, in fact serves as a measure for the total losses from the economic cycle. Its contribution to the total materials use, either approached by V/M or by D/M, thus equals the leakage fraction of the economic system. Therefore its counterpart R/M, the fraction of the total materials use that is accounted for by secondary materials, is a measure of the efficiency of the economic system as a whole.

The two calculating procedures lead to different outcomes: with the first procedure (V/M), the relative leakage is 69%, while the second procedure (D/M) yields 36%. A small part of the difference is caused by the fact that procedure 1 includes the leakages in the recovery and production stage, while procedure 2 does not. Apart from that, the two indicate slightly different aspects: procedure 2 is indicative of a region's waste treatment system, while procedure 1 indicates the whole chain, which is heavily influenced by global aspects. One conclusion could be, therefore, that the Netherlands contribute to a better copper management on a global level.

As target levels, a 100% secondary input and 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 environmental indicators. As a relative indicator, the lower leakage percentage will be the better one.

Indicator 4: the efficiency of the life-cycle stages

While, as Figure 4.2 shows, OUT/IN makes no sense for the system as a whole, it may be useful to establish a leakage percentage in this manner for each step in the life cycle, viz. extraction and refining; product manufacturing; use and consumption; and waste processing. The inverse of this leakage percentage then is the efficiency: the fraction of the inflow that ends up in a useful form of outflow. The efficiency indicator obviously is of the "combination" type.

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" stage, 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" stage 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" stage'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 step a leakage loss can be determined, and then expressed as total losses/total input. The actual definition of the subsystems, the life-cycle stages, is the most difficult part. With the wisdom of Figure 4.2 as a point of reference, a first rule is to define the various steps or 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.

A third issue is the classification of the various output flows: when should a flow be considered a leakage, and when a useful output? For this, 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 cycle study on metals, 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 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.

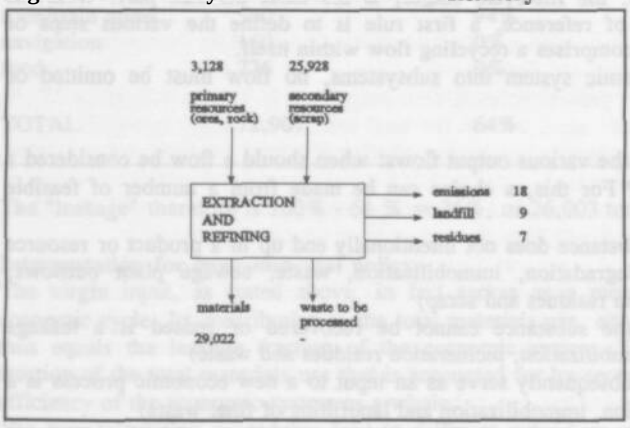
A fourth issue is the economic accumulation which is neither a "useful" outflow nor yet a loss from the economic cycle. To elude this problem, calculating the long-term steady state may prove to be the best basis for the comparison of different regimes: it is the situation in which the ultimate fate of the accumulation is determined and all of the inflow can be attributed to either a useful outflow or a leakage.

In Figure 4.3, 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. Figures 4.4, 4.5, 4.6 and 4.7 can serve as general schemes for the various subsystems. The figures refer to the actual situation regarding copper in the Netherlands in 1990 (not to the steady state situation connected with the 1990 regime), and are expressed in tonnes Cu/year. In Figure 4.6, IN does not equal OUT, due to accumulation taking place in this subsystem. The subsystems do not connect, due to imports and exports.

Subsystem Extraction and Refining

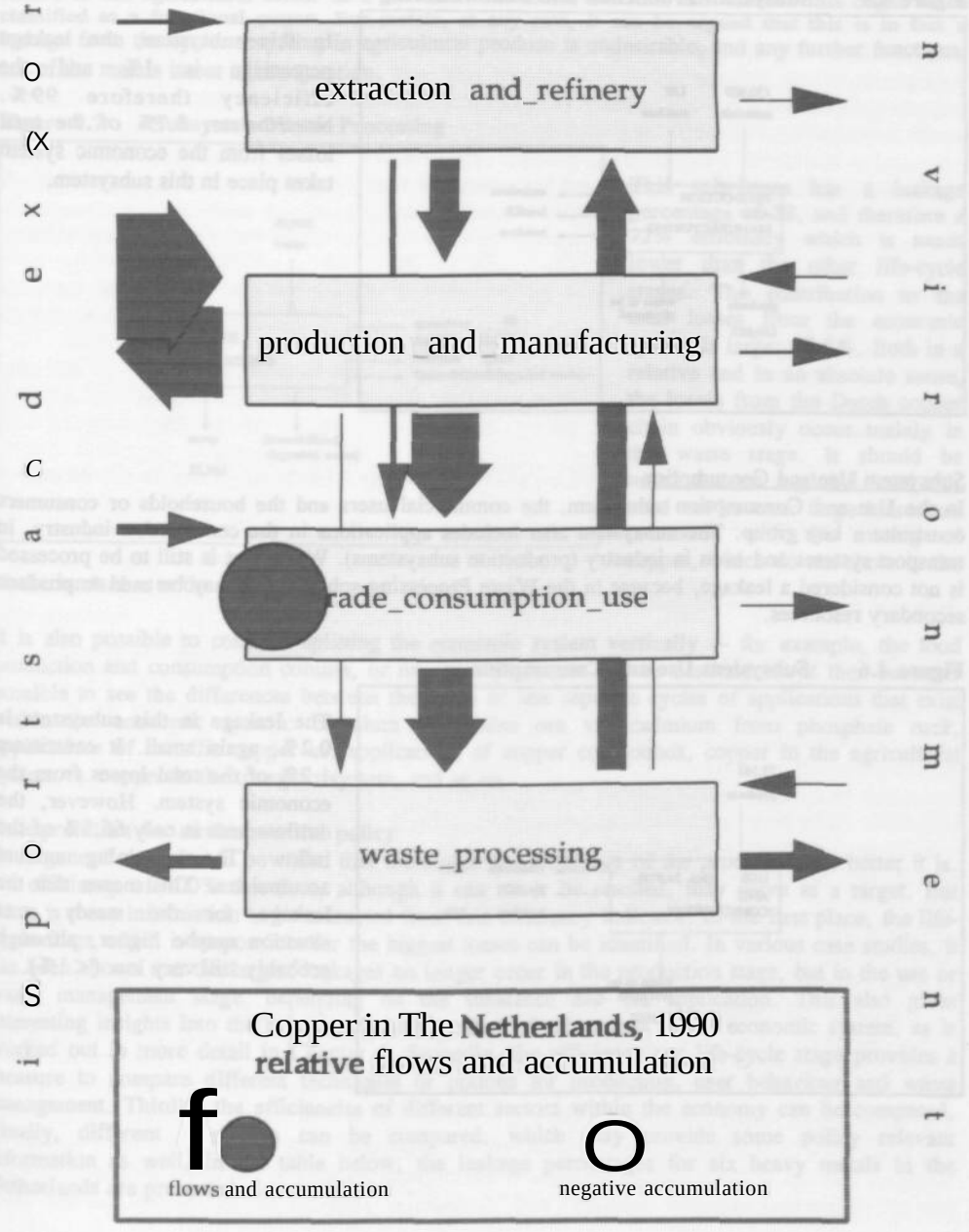
The Extraction and Refining subsystem contains processes with regard to mining and refining. Also, the secondary recovery of substances from scrap or compound waste forms a part of this system.

Figure 4.4 Subsystem Extraction and Refinery



This means a leakage percentage of 0,1% and, inversely, and efficiency of 99,9%. 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.

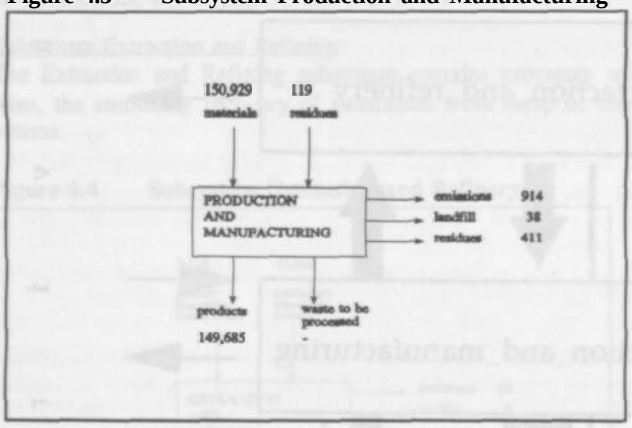
Figure 4.3 The economic copper cycle for the Netherlands, 1990



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 4.5 Subsystem Production and Manufacturing

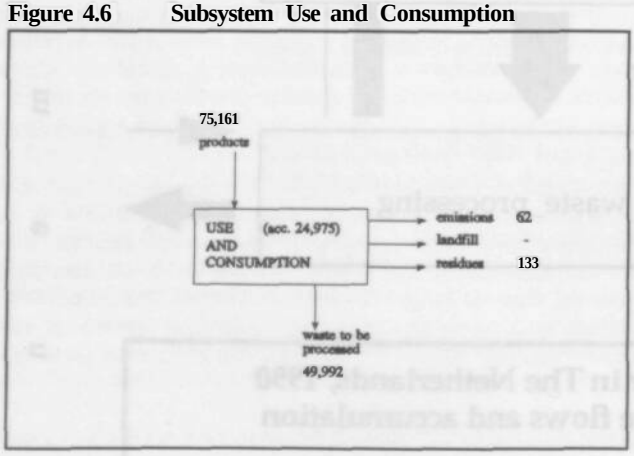


In this subsystem, the leakage percentage is 1% and the efficiency therefore 99%. Nevertheless, 8.7% of the total losses from the economic system takes place in this subsystem.

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 4.6 Subsystem Use and Consumption

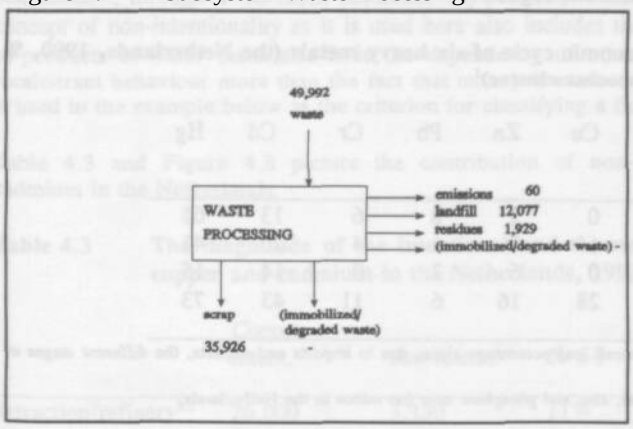


The leakage in this subsystem is 0,2%, again small. It constitutes 1.2% of the total losses from the economic system. However, the outflow here is only 66,5% of the inflow. The remaining amount accumulates. This means that the leakage for the steady state situation maybe higher, although probably still 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 4.7 Subsystem Waste Processing



This subsystem has a leakage percentage of 28, and therefore a 72% efficiency which is much lower than 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.

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.

Interpretation for environmental policy

As a general rule, it can be stated that the higher the efficiency of the processes, the better it is. An efficiency of 100% therefore, although it can never be reached, 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. This also gives interesting insights into the behavioral characteristics of substances in the economic system, as is worked out in more detail in Chapter 6. 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 the table below, the leakage 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 under Indicator 5. For lead, the recycling percentage is highest. For zinc, the low losses in the waste stage are 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 losses from the waste stage 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 under Indicator 7: problem shifting to other regions.

Table 4.2 Losses from the economic cycle of six heavy metals (the Netherlands, 1990, % of input into each process cluster)[1]

Metal / *Life-cycle stage*	Cu	Zn	Pb	Cr	Cd	Hg
Extraction/refining[2]	0	2	8	6	13	61
Production/manufacturing	1	3	1	4	20	41
Use/consumption	0	6	2	0	14	15
Waste treatment	28	16	6	11	43	73

[1] The percentages may not be added to one overall loss percentage since, due to imports and exports, the different stages of the life cycle do not connect.
[2] Only recovery from scrap and refining of iron, zinc and phosphate ores (no mines in the Netherlands)

Indicator 5: the relative magnitude of non-intentional applications

As stated above and treated in more detail in Chapter 6, it is very important for environmental policy to allow for the problem of non-intentional flows within the economic system, i.e. flows of the substance caused wholly or partly by forces other than the demand or need for the substance itself. Non-intentionality may occur at all stages of the life cycle: recovery as an ore contaminant, or less extremely as a by- or co-product, application as a product contaminant, occurring as a non-functional or even unwanted trace in food products, or non-intentional recycling in waste residue materials. Shifts from intentional to non-intentional also occur: the cadmium, recovered initially as a by-product of zinc, is intentionally extracted from zinc ore and applied in batteries, while the intentionally applied pig feed copper additive ends up unwanted in slurry. In secondary materials such as manure, compost, fly ash, scrap and suchlike, there are often large quantities of pollutants unintentionally starting their second life cycle. While the intentional flows can be addressed more or less effectively by a policy directed at the intentional applications of the substance, this is less obvious for the non-intentional ones since the "normal" relationships of supply and demand cannot be applied to the substance any more. Moreover, the non-intentional applications often are of a rather dissipative nature and therefore are more at risk of leaking from the economic cycle to the environment unnoticed.

The significance of the indicator

The magnitude of the non-intentional flows vs. the intentional ones indicates the level of risk of measures directed at the substance will lead to an unsuspected shift of the problem, due to the fact that the (implicitly) expected "upchain" and "downchain" relations are not present. In this case,

"intentionality" indicates "manageability", and a substance with a non-intentional cycle of any relevance can be characterized as a recalcitrant substance.

Method of calculation

This indicator is related to the efficiency indicator presented before, in the sense that distinctions among the different stages of the economic life cycle are proposed once again: extraction, production, use and waste management. Non-intentionality in each of these stages leads to different policy implications, as is illustrated by the case of cadmium (see Chapter 7). For each of these stages, a percentage of non-intentionality can be calculated, according to *non-intentional inflow/total inflow*. For every separate inflow, the intentionality must therefore be determined on an either/or basis, although in reality this is a sliding scale, from a truly non-intentional contaminant, through a "so much the better" by-product, to an in fact intentional co-product. The concept of non-intentionality as it is used here also includes the recovery of materials as by- and co-products of other materials. It is the dependency of other "host" materials that causes the recalcitrant behaviour more than the fact that money is made out of it. This dependency therefore is used in the example below as the criterion for classifying a flow as non-intentional.

Table 4.3 and Figure 4.8 picture the contribution of non-intentional flows for copper and cadmium in the Netherlands.

Table 4.3 The magnitude of the intentional and the non-intentional economic cycle for copper and cadmium in the Netherlands, 1990.

	Copper			*Cadmium*		
	intent.	non-intent.	% n-i	intent.	non-int	% n-i
extraction/refinery[1,2]	26,000	3,130	11%	742	0	0%[3]
production/manuf.	151,000	522	0.3%	6	20	77%
use/consumption	75,000	5,400	7%	221	17	7%
waste treatment	50,000	283	0.6%	86	19	18%
accumulation	22,000	5,370	20%	+80	-6	-
emissions[4]	139	1,220	90%	1	16	94%
total chain losses[5]	11,979	3,746	24%	42	126	75%

[1] Only recovery from scrap and refining of iron, zinc and phosphate ores (no mines in the Netherlands)
[2] The figures refer to the inflow into the subsystem. Due to imports and exports, the subsystems do not connect.
[3] Recovery of cadmium from zinc ore is intentional; no zinc mines in The Netherlands.
[4] Emissions to the atmosphere, surface water and diffusive soil emissions
[5] Emissions and landfill.

It can be seen from Table 4.3 and Figure 4.8 that for both cadmium and copper the losses from the non-intentional economic cycle are considerably larger than from the intentional one. For cadmium, this is not very surprising since the non-intentional cycle is relatively large. For copper however the non-intentional cycle, although responsible for the majority of the emissions, is relatively small.

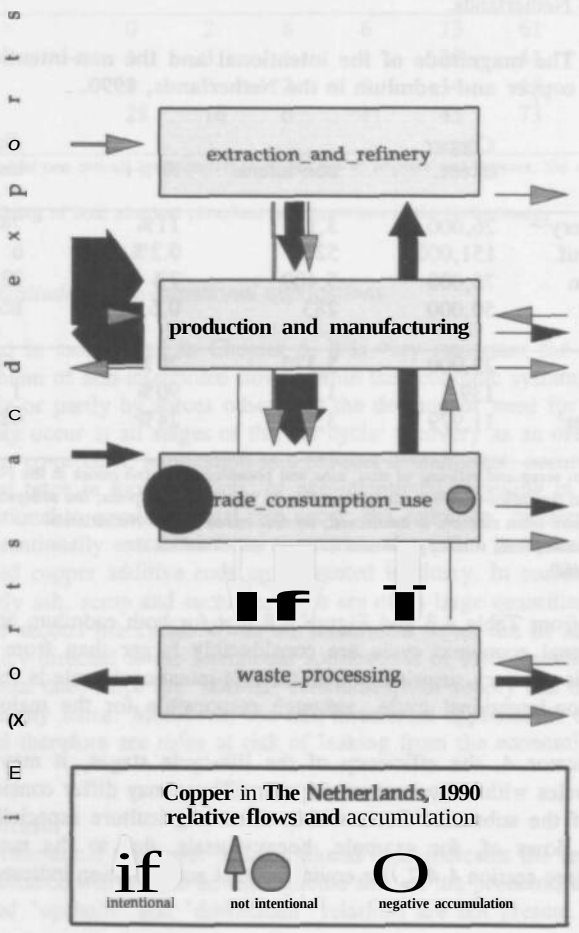
Similar to Indicator 4, the efficiency of the life-cycle stages, it may be useful to distinguish different sub-cycles within the economic system. These may differ considerably with regard to the intentionality of the substance flows within them. Agriculture especially is known for its large non-intentional flows of, for example, heavy metals, due to the mechanism of "closed loop accumulation" (see section 4.4.2, the environmental accumulation indicator).

Interpretation for environmental policy

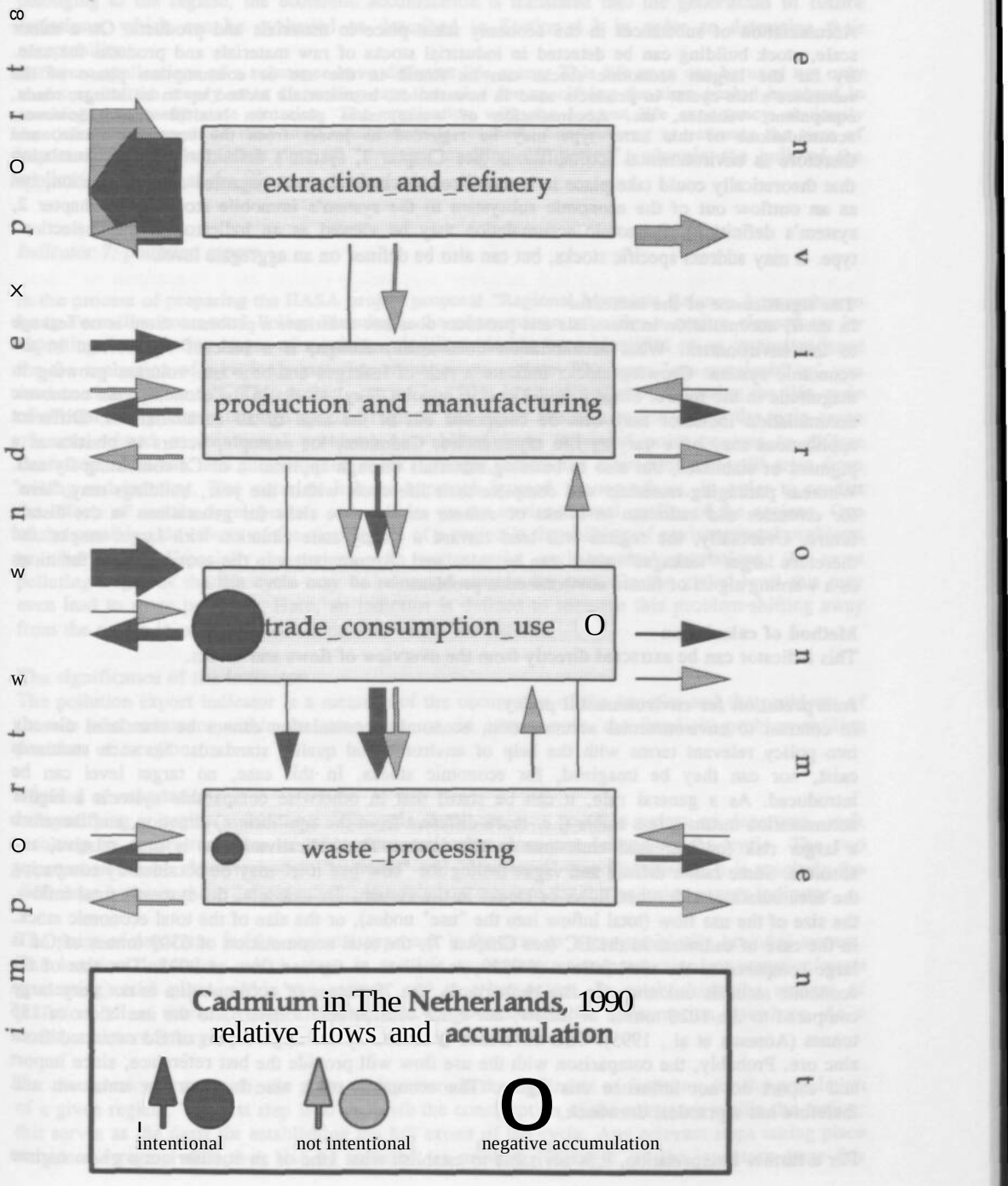
It can be stated that a higher contribution of the intentional flows to the total cycle means a higher probability that a "straightforward" substance policy will be effective. A significant non-intentional percentage indicates that additional measures are required, related to the "host" ore, material, product, or residue involved. There is no question of any desired ratio. In principle, it is desirable to avoid non-intentional applications as much as possible. However this guideline, if carried out to the extreme, might lead to the ending of recycling practices for fly ash, slag, compost, sewage sludge and suchlike, and might therefore seriously cripple a waste management policy. Moreover, non-intentional applications cannot in all cases be prevented: as long as zinc is used, cadmium will occur as a contaminant, and while copper is applied intentionally in pig feed, it inevitably ends up unintentionally in pig slurry. The life-cycle stage in which the non-intentionality occurs is important for the formulation of a successful substance management policy. Again, it is not possible to define a reference value. The implications for a substance management policy are discussed in more detail in Chapter 6, and also in the case study on cadmium (Chapter 7).

Figure 4.8 **Intentional and non-intentional flows in the various life-cycle stages for copper and cadmium in The Netherlands in 1990.**

4.8a **Copper**



4.8b Cadmium


extraction_and_refinery
production_and_manufacturing
trade_consumption_use
waste_processing
Cadmium in The Netherlands, 1990
relative flows and accumulation
intentional
not intentional
negative accumulation

Indicator 6: Economie accumulation

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 may be regarded as losses from the economic chain, and therefore as environmental accumulations (see Chapter 2, system's definition). The accumulation that theoretically could take place in immobilized stocks is also not regarded as accumulation, but as an outflow out of the economic subsystem to the system's immobile stocks (see Chapter 2, system's definition). Economic accumulation may be viewed as an indicator of the "selection" type. It may address specific stocks, but 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 equilibrium) 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. In the case of cadmium in the EC (see Chapter 7), the total accumulation of 6309 tonnes of Cd is large compared to the total inflow of 9829, as well as to the use flow of 9033. The size of the economic stock is unknown. In the Netherlands, the 79 tonnes of accumulation is not very large compared to the 1020 tonnes of inflow, but again considerable compared to the use flow of 185 tonnes (Annema et al., 1995). This difference is caused by the large export of Cd extracted from zinc ore. Probably, the comparison with the use flow will provide the best reference, since import and export do not influence this figure. The economic stock size is generally unknown and therefore has a practical drawback.

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 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 .

Indicator 7: pollution export

In the process of preparing the IIASA project proposal "Regional Materials Balance Approaches to Long-Term Environmental Policy Planning", the phenomenon whereby a region cleaned up by exporting the polluting stages of a substance's life-cycle has been identified as an important issue for the evaluation of a region's materials management regime. The term "net-sustainability" was used to characterize this. This project, started in 1994, is concerned with following the life cycle of several heavy metals through specific regions: the Rhine Basin, a region where the main cause of metal-related environmental problems has shifted from industrial point sources to diffuse consumer emissions, and the so-called Black Triangle, where the main problems still arise from mining and industry. The materials balance approach is used, among others, in order to predict the effects of certain developments and policies on the environmental quality of the regions. 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. 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 export indicator 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" (see Chapter 2). 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.

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 "LCA 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.

In theory, subtracting the "regional" leakages from the "functional" ones would provide an accurate measure of the net pollution export. A pollution importing country thus harbours emissions for the benefit of other countries, while a pollution exporting country farms its leakages out to other countries. It is useful to chart these; the extra risk (offset by extra income) is then a conscious risk or, vice versa, the buying off of environmental problems is made explicit. 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 this pollution export indicator, "space" must be taken metaphorically. Instead of "the Netherlands actually occupies three times its actual territory", the conclusion could be something along the lines of "the Netherlands is in fact responsible for three times the pollution that it actually has within its borders".

In practice, this approach makes 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., 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. 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.

To move one step further in the direction of a real pollution export indicator, 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.

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 4.4 Self-sufficiency and pollution export for copper in the Netherlands

	1990			2010, accepted and intended policy		
	s.s.[1]	leaks[2]	ref.[3]	s.s.	leaks	ref.
extraction	38%	34	90	60%	31	52
manufacturing	199%	1363	685	210%	873	416
consumption	100%[4]	195	195	100%	208	208
waste processing	100%	14133	14133	100%	8672	8672
TOTAL leakages		15725	15103		9784	9348
net export of leakages[5]		-622			-436	
pollution export indicator[6]		-4%			-4%	

[1] self sufficiency per life-cycle stage, obtained by dividing the regional total input by the reference total input per life-cycle Mage

[2] regional leakages, occurring within the borden of the region, in tonnes/year, obtained from the SFA overview of flow» and stocks

[3] reference leakages, 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)

[4] consumption, as the starting point, automatically has a self-sufficiency of 100%

[5] obtained by subtracting the TOTAL regional leakages from the TOTAL reference leakages

[6] obtained by dividing the net export of leakage» by the TOTAL reference leakages

Interpretation for environmental policy

A reference value of a 0% pollution export would seem a logical choice. However, the problem-exporting or problem-importing practices of a region cannot in all cases 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. The self-sufficiency and pollution export indicators can be used more sensibly 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.

4.4.4 Indicators concerning the system as a whole

If we regard the region as a whole, integrated over the economy and the environment, a very important aspect concerns the basic functions of the environment for the economy. In a study for the Dutch government concerning Natural Resource Accounting (Huele et al., 1993), various indicators were selected and redefined so that they had greater relevance to the functions fulfilled by natural resources. For material resources, two groups of functions are distinguished: the *source* function, relative to the availability of the resource for human consumption, and the *life support* function, related to the capacity of the environment to provide livable surroundings. For the source function, resource depletion is the main environmental problem. This is covered in part by Indicator 3 as discussed above. For the life support function, the disruption of the natural cycle of the substance and the consequences of that constitute the most pressing problem, at least if we limit ourselves (as we do in this publication) to resources in the shape of substances. This second

possibility is worked out below.

Indicator 8: natural vs. economic cycle

The disruption of natural substance cycles may be caused by either large extractions from the environment which cannot be replenished adequately, or large additions to it in the shape of emissions. The indicator presented here addresses the latter possibility: disruption by addition. This indicator has most relevance for substances involved in an important natural cycle, such as carbon, nitrogen, phosphorus or sulphur. For elements that occur in the environment "naturally" only in small quantities or not at all, such as heavy metals, dioxins or pesticides, the addition to the environment caused by humans will soon be relatively large and the calculating of an indicator has little meaning. The indicator thus can be related to the study of elements which are part of the grand biogeochemical cycles, and the transformation of those cycles into "anthropo-biogeochemical" cycles.

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):

$$\frac{\text{emission from the economic subsystem (kg/y)}}{\text{generation within the environmental subsystem (kg/y)}}$$

For N in the Netherlands, a case in point worked out during the NRA study, the emission amounted to respectively 64 (in 1986) and 47 (in 1990) times the natural fixation. These are very large numbers, indicating that the nitrogen inflow into the Dutch environment is 98-99% anthropogenic. A promising development seems to be the lowering of this ratio in recent years.

A second way to provide an indication for the risk of disturbance of the natural N-cycle is to compare the respective magnitudes of the economic and the ecological cycles. A relatively large economic cycle then constitutes 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 nitrogen *use.* The process can be complicated by separating the use of 'virgin' nitrogen from the relatively large turnover in natural ecosystems. Also, the natural stocks of nitrogen compounds in soil and groundwater are a factor 10^7 larger than the annual natural fresh input. It is necessary to determine whether recycling flows from these stocks should be included in a calculation of the magnitude of the natural cycle; there are arguments in favour as well as against inclusion. A comparison based on fresh input for use within the system leads, for the Dutch situation, to the rather frightening number of 110: the economic cycle is, thus calculated, 110 times larger than the natural cycle (vs. 1, equally large, on a global level).

On a global level, the two approaches differ only with regard to the degradation in the economy, since imports and exports are not relevant and in the case of nitrogen no appreciable accumulation occurs in the economic system. The first approach therefore is the approach the brings us closest to what we want to know, i.e. the risk for disruption of the natural cycle by over-addition. The second approach has the advantage of being easier to establish: less data are required, and no border definition problems will occur. If used as a relative indicator, both may prove adequate.

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.

4.4.5 Discussion and conclusions

In Section 4.4, a number of indicators for integrated substance chain management have been defined, based on the outcome of a substance flow analysis with a sometimes limited amount of additional information. This is presented as a possible procedure for element 3 in the general SFA framework: the interpretation of the SFA results. The indicators discussed in the previous sections cover various aspects of a region's materials management. Although sketchy, this means a further step along the road toward judging especially the *economic* substance flows and their potential environmental risks, for which measures and indicators are scarce at present. It can be stated that there are many discussions which remain still unfinished or which have not even been started with regard to the calculation procedure and the simplifications that need to be made, and with regard to the actual value of these indicators. There is a decided lack of reference values, even for the environmental flows. In most cases, the indicator can really only be used to compare ("less is better") and not to judge absolutely. If it were possible to calculate the environmental impacts of every regime change with the right amount of detail, some indicators might become superfluous. However, the scale levels of the environmental problems related to substances and environmental policy hardly ever coincide. Moreover, it can have great communicative power to sum up a region's substance chain management in a few relevant measures even if it would be possible to comment on what we really want to know, i.e. the actual environmental consequences. Therefore, indicators directed at economic substance flows will be useful in any case.

4.5 Generalization: A comprehensive procedure for evaluating a region's substance management regime

In Section 4.1, four categories of problems, which may be addressed by SFA studies, have been formulated. In sections 4.2, 4.3 and 4.4, an attempt has been made to define modes of translation of the SFA overview into information regarding these categories. In this section, some attention is given to the evaluation of a region's materials management *as a whole. A* distinction can be made between the analysis of the *causes of* certain pollution problems already present in the region, and the analysis of the *consequences* of certain economic substance management regimes.

For the analysis of current problems related to the substance under study, the origins analysis as described in Chapter 3 is promising. With that approach, the direct causes, the economic sectors responsible, and the ultimate origins of pollution problems can be traced. Generally, this offers adequate opportunities to formulate a relevant management strategy, which can be checked by calculating the effects of this new regime on the substance flows and stocks within the region.

The best approach for evaluating the consequences of a certain substance management regime seems to be to translate the overview into a standardized, limited set of indicators, which as a group must provide an adequate measurement of the situation and of the impacts of policy measures. A general outline for such a set could be sketched rather easily: *a comprehensive set should provide adequate information regarding the presumed economic substance regime of a region and its possible consequences for depletion of resources and for pollution problems, thereby including aspects of problem-shifting.* The following is a first, still very general, proposal for such a set:

Depletion

- total economic virgin input of the substance (not worked out separately, but part of Indicator 3, primary/secondary materials use)
- contribution of the region to (global) depletion of mineral resources, absolutely and per inhabitant (not worked out here)

Pollution

- occurrence of pollution within the region: confrontation of selected flows (emissions or environmental flows) with regional environmental quality standards or targets (as worked out in 4.3, and also in the case of nitrogen, chapter 6)
- totalized losses and totalized emissions respectively from the economic chain/cycle (not worked out here)
- risk of the economic cycle disturbing natural substance cycles (worked out in 4.4.4, economic vs. natural cycle)
- pollution caused by the region: contribution of regional emissions to fluvial, continental or global pollution problems, absolutely and per inhabitant (example discussed in 4.4.2: mineral surplus. Also in 4.3: introduction of equivalency factors)

Management

- efficiency of economic substance life-cycle (worked out in 4.4.3 as efficiency of life-cycle stages and as primary/secondary materials use)
- totalized economic use level: either flow or stock (not worked out here)
- recycling percentage (worked out in 4.4.3, indicator no. 3)

Problem-shifting

- within the area: the chance of policy measures not working out as expected (worked out in 4.4.3, the non-intentionality indicator)
- to the future: accumulation in the environment and accumulation in the economy (worked out in 4.4.2 and 4.4.3)
- to other regions: global shift - confrontation of pollution/depletion in region with pollution/depletion caused by region (worked out in 4.4.3. the pollution export indicator)

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. Problem-shifting, for example, 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 problem of weighing the relative merits of the indicators would become pressing indeed if our aim was the integration of the set of indicators into one value or index for the integrated environmental risks of an economic substance chain regime. At present, no attempt is being made to do so. In the future, however, this will almost certainly return as an important issue.

4.6 References

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PART III SUBSTANCE FLOW ANALYSIS AND SUBSTANCE POLICY

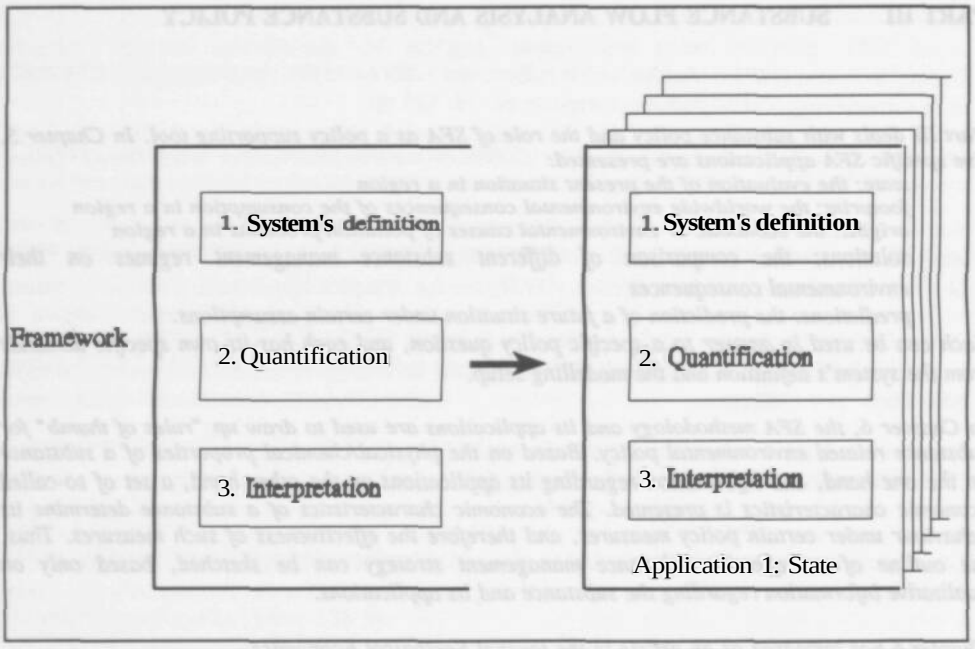
Pan III deals with substance policy and the role of SFA as a policy supporting tool. In Chapter 5, five specific SFA applications are presented:

- ***state: the evaluation of the present situation in a region***
- *footprint: the worldwide environmental consequences of the consumption in a region*
- *origins: the economic or environmental causes of pollution problems in a region*
- *solutions: the comparison of different substance management regimes on their environmental consequences*
- *predictions: the prediction of a future situation under certain assumptions.*

Each can be used in answer to a specific policy question, and each has its own specific demands from the system's definition and the modelling setup.

In Chapter 6, the SFA methodology and its applications are used to draw up "rules of thumb" for substance related environmental policy. Based on the physical/chemical properties of a substance on the one hand, and information regarding its applications on the other hand, a set of so-called economic characteristics is presented. The economic characteristics of a substance determine its behaviour under certain policy measures, and therefore the effectiveness of such measures. Thus, the outline of an effective substance management strategy can be sketched, based only on qualitative information regarding the substance and its applications.

Chapter 6 has appeared as an article in the journal Ecological Economics.


Framework
1. System's definition
2. Quantification
3. Interpretation
1. System's definition
2. Quantification
3. Interpretation
Application 1: State

CHAPTER 5 FIVE SFA APPLICATIONS FOR ENVIRONMENTAL POLICY

5.1 Introduction

In Chapter 2 it is stated that while the general framework is applicable for all SFA type studies, the details must be considered separately in each case, and both the system's definition and the modelling options must be chosen from the point of view of the desired outcome of the study.

In this chapter, this statement is taken a step further by collecting the various purposes for which SFA has been used during the research for this thesis, and specifying the choices for each of those SFA applications. SFA has been applied in case studies, more or less implicitly, to obtain an answer to different specific questions. In this chapter, five different types of SFA applications are distinguished. This list of five arises from the experience of the case studies conducted to date. It is not meant to be comprehensive; so far, every case study has added to the list. New questions of course have new implications, for every question that arises the choices must be made explicitly. In Section 5.2, the five SFA applications are treated:

- *state:* the evaluation of the present situation in a region, in 5.2.1
- *footprint:* the worldwide environmental consequences of the consumption in a region, in 5.2.2
- *origins:* the economic or environmental causes of pollution problems in a region, in 5.2.3
- *solutions:* the comparison of different substance management regimes on their environmental consequences, in 5.2.4
- *predictions:* the prediction of a future situation under certain assumptions, in 5.2.5.

As a sixth "application", the overall evaluation of a substance regime can be mentioned. This application, which is treated in 5.3, differs from the others in that it does not cover one aspect of a substance regime, but tries to be comprehensive. As such, it can be applied to all types of systems and to an overview obtained by any type of modelling.
In section 5.4, the results are summarized in an overview table.

5.2 The different SFA applications and their requirements

For each of these SFA applications, the three steps of the framework are discussed, and the methodological decisions to be made are specified.

System's definition
The applications each have their own appropriate system's definition. This definition is closely linked to the third step of the framework, the *interpretation.* Decisions to be made concern:

- the regional or the functional approach
- the geographical demarcation of the region
- the encompassing of both environment and economy, or the limitation to just the economic subsystem
- the further subdivision of the subsystems.

Modelling choices
In Chapter 3, some conclusions are drawn with regard to the three types of modelling that have been distinguished - bookkeeping, static modelling and dynamic modelling - and the use that these can be put to. Based on the evaluation of the case studies in this chapter, some more specific recommendations can be added with regard to the choices that must be made and how these depend on the aim of the study, or in other words, the type of conclusions that one wishes to

draw from an SFA study. These recommendations refer to:

1. Most appropriate type of modelling
2. Most suitable choice of fixed variables
3. Need for taking stocks into account
4. **Derivation of distribution coefficients**
5. **Preferred choice of balancing items.**

Interpretation of the results

The main question here is whether the specific application requires an absolute evaluation (conforming to targets, good enough measures), or whether a relative evaluation will suffice (decreasing flows, better measures). Specific applications may, as stated above, demand a specific system's definition.

5.2.1 State: the evaluation of the situation in the present or recent past

Monitoring the state of the environment has always been an important part of environmental policy. Keeping track of substance flows can be, and in some cases has been, a part of that. By accounting for substance flows regularly, it becomes possible to follow developments, to verify predictions, to spot trends, and to become aware of potential future problems. Monitoring frequently also keeps the possibility open for observations of the unexpected. An evaluation of the situation thus has two aspects, (1) the present state of the environment and deviations from the desired state, and (2) the direction of the developments through time and deviations from the desired direction.

System's definition:

This SFA application is closely linked to national environmental policy, which is concerned with the state of the environment within its territory. A regional approach is therefore indicated, and a scale level that is relevant in any case is the national level. In some cases, it could be useful to keep track of substance flows on a higher (groups of countries) or lower (counties, polders) administrative scale level as well. It can also be useful to observe an ecologically bordered system, such as a river basin, a lake or inland sea, or a coastal sea. Monitoring of both economic and environmental flows is relevant. The developments in time can only be followed if repeated frequently. The actual frequency may vary with the substance. It makes the most sense to let the choice regarding the substance or substance group to be observed be inspired by the environmental problems related to the substance. On the other hand, the nature of the substance must be taken into account: if the economic chains are short and simple, no SFA is required, but a record of the emissions and environmental processes will be adequate. This is the case, for example, with pesticides. Keeping track of substances with durable applications, i.e. applications having a lifetime of more than one year, is especially useful, since in these cases there may be a considerable delay in the reactions to regime changes. Metals are examples of such substances.

Quantification of the overview:

An evaluation of the actual situation and following developments throughout the years should be based as much as possible on statistical and monitoring data. Only real observations lend themselves to an evaluation of the situation with regard to policy goals and targets. For the choices that must be made in the *quantification* step, as described above, this means the following:

1. Type of modelling: bookkeeping system, present year, repeated frequently
2. Fixed variables: - (as many as possible in a bookkeeping system)
3. Stocks: preferably including stocks in the overview
4. Distribution coefficients: - (not applicable for a bookkeeping system)

S. Balancing items: the balancing option can be used for data check or estimate of missing variables.

Interpretation of the results:
The interpretation of this SFA application refers to two issues: the present situation, and the developments in time. For an evaluation of the present situation, a confrontation of the emissions and environmental flows with criteria such as quality standards or policy targets is required. Sometimes, a translation must be made: either the flows must be translated into concentrations, or the concentration-based targets must be translated into acceptable flow levels. Evaluating developments in time is less demanding. Trends, i.e. decrease or increase of specific flows through time, can be spotted automatically by comparing different years. Recovering the influence of past developments and policies is probably more difficult.

5.2.2 "Footprint": the global environmental consequences of a region's consumption

The concept of "footprint" refers to the environmental space that is occupied by a region, if all activities for the fulfilment of the needs of the population of that region are included as well. "Space" can be taken literally if it concerns, for example, agriculture. If the use of resources and the generation of pollution is the issue, "space" is used metaphorically. One issue is to establish whether the population of a region uses up more resources, or causes more pollution than the global average. The basis of comparison then can be the pollution or depletion score per capita. Another possibility is to compare the amount of resource extraction and pollution occurring within the region with the amount occurring, wherever in the world, on behalf of the region's population. In that way, insight is obtained as to the location of this metaphorical footprint, or in other words, whether the environmental costs and the economic benefits of the use of materials occur in the same area. This last option is introduced in Chapter 4 as the pollution export indicator.

System's definition:
In establishing a region's footprint on a per capita basis, the system must be defined according to the functional approach. The use and consumption level of the region is the starting point, the extent of the other phases of the life cycle is derived from this use level. If calculating the pollution export indicator, two systems are compared: the regional system with the functional system. It is easier and probably sufficient if only the economic subsystem is being taken into account, with resource extraction on the inflow side and emissions on the ouflow side. The economic subsystem must be divided into the phases of the substance's life cycle, with at least three separate parts: the use and consumption phase, the phases before, and the phases after that. A further subdivision is of course possible. The choice for substances or substance-groups again must be inspired by the environmental problems, but also by the conviction or suspicion that the region's footprint differs significantly from either the global average, or the actual situation in the region.

Quantification of the overview:
For this application, too, a picture of the actual situation in the present is required. Again, this means that the overview of flows and stocks must be based, as much as possible, on statistical and monitoring data. However, in this case it is often much more difficult to obtain the required data, since these must come from all over the world and generally must be derived or extracted from aggregate data. In Chapter 4, an escape procedure is proposed, which enables one with some rough assumptions to draw conclusions from regional data only. If the per capita approach is taken, then the pollution or resource requirement per capita must be known on the global level in

order to compare. This constitutes less of a problem, in general, since global data are available for a number of substances. The modelling requirements are similar to those of 5.2.1:

1. Type of modelling: bookkeeping, present year
2. Fixed variables: -
3. Stocks: not required.
4. Distribution coefficients: - ; if necessary, the *functional* flows can be calculated from the *regional* ones by simple multiplication factors.
5. **Balancing items: the balancing option can be used for data check or to estimate missing variables.**

Interpretation of the results:
Depending on the approach taken, the interpretation is either the share of the regional population using the world's resources and polluting the environment, or the amount of pollution import or export of the region. Both can be a measure for the regional population's welfare at the expense of the environment of others, or the other way round. This SFA application is closely linked to one of the indicators, the *pollution export* indicator, described in Chapter 4.

5.2.3 Origins: the economic and environmental causes of pollution in a region

The origins analysis aims at specifying the causes of specific pollution problems. In Chapter 3, the origins analysis as it is applied in the case studies and implemented in the computer program SFINX is explained. Three levels of origins of pollution are distinguished: the direct causes, the economic sectors responsible, and the ultimate origins that lay on the inflow border of the system. This information is important for a pollutants policy: not only the direct causes, the emissions, must be known, but also the actors that cause them, the target groups for environmental policy. The ultimate origins must be known as well: abatement measures can only be effective if the ultimate origins are affected by it, either directly or indirectly, as is shown in both of the case studies.

System's definition:
The origins analysis is relevant only for regionally defined systems. It can be applied on any scale level, but the relevance of the information is limited for the global as well as the local level: on the global level, every instance of pollution ultimately can be traced back to the mines, while on the local level everything comes from transboundary inflow. Since this analysis is meant to link environmental flows to their economic origins, both economy and environment must be included in the systems definition. Defining subsystems in this case serves no purpose, not even the economic and environmental subsystem.

Quantification of the overview:
As already stated in Chapter 3, for the origins analysis a modelling of the relations between the various flows is required. It is the physical causality that counts in this case, the ultimate sources lay at the beginning of the substances life cycle. Therefore, the inflow variables must be the fixed variables from which all others are calculated. The model will mostly reflect the situation in the present or recent past, since policy will be primarily interested in the origins of present pollution problems. A problem arises with regard to aspects of time: emissions from accumulated stock cannot be traced back in time to their earlier life cycle stages. Therefore, stocks cannot be included in the analysis. This means that the analysis must integrate over time in case of such delay problems. This is hardly possible in practice. Two solutions present themselves: one is considering emissions from stock as a system's source, the other is ignoring the stocks and

calculating the nodes' outflows from its inflows only. Summarizing:

1. Type of modelling: static model, present year
2. Fixed variables: the system's sources
3. Stocks: it is impossible to include stocks other than as sources, since these represent a time delay which cannot be introduced into the model for the starting year
4. **Distribution coefficients: according to physical/technical causality**
5. **Balancing items: if possible according to physical/technical reality (accumulations).**

Interpretation of the results:

The result of the origins analysis is the absolute and relative contribution of the various categories of flows to the selected problem flow. No further interpretation is required.

5.2.4 Solutions: the comparison of different substance management regimes on their environmental consequences

One SFA application concerns the scanning of different possibilities for changing substance management regimes. Before deciding on which course to follow, an insight in the consequences of such a course is required. One of the aspects that is important is time: the period it takes before cenain measures become effective, and the situation in a specific future year with or without regime changes. For this, a *prediction* is required, which is treated in Section 5.2.5. Another, and more important, aspect concerns the ultimate or intrinsic consequences of a regime. It may be that a certain regime leads to a cleaning up in the short term, but it won't be better in the end, or it may even be worse than the present regime. This may not show in a prediction, unless it is a prediction for infinity. Instead of predicting infinity, the ultimate consequences of a regime can be estimated quite easily by calculating the steady state situation belonging to the regime. Thus, a picture emerges of the eventual direction and magnitude of the changes. In this way, different regimes can be compared with the present one and with each other in order to decide on their ultimate desirability.

System's definition:

The comparison may be made with regard to different aspects of the regime (see under *Interpretation of the results).* In the first place, the system must be defined from the regional approach, on the scale level relevant for policy. In principle, both economy and environment are relevant. One may considering looking only at the economic subsystem; an overview containing environmental flows may suggest that they be regarded as predictions. If the regimes are evaluated on their consequences for problem shifting to other areas, an additional functional definition of the system and a division of the economic subsystem into the stages of the life cycle is required (see Section 4.3.3, indicator 7).

Quantification of the overview:

To compare different regimes, the reaction of the model to changes must be, as much as possible, in accordance with reality. In this case, reality means economic causality. Economic aspects such as elasticities of supply and demand are driving forces here. The economic characteristics of the substance, as they are delineated in Chapter 6 hereafter, can be important in determining how to set up the model. However, physical/technical causality must not be lost, since "downchain" from consumption, i.e. waste generation and environmental flows, no economic laws apply. The same is true for the technical aspects of production processes, including emission factors. As stated before, the steady state situations belonging to the different regimes offer the best basis for comparison, since mechanisms of delayed impacts have disappeared and data problems regarding stocks have less influence over the flows. Modelling requirements are:

1. Type of modelling: static model, steady state situation
2. Fixed variables: either the system's sources, or the demand/required stock, according to the economic substance characteristics
3. Stocks: preferably including stocks
4. Distribution coefficients: economic causality, but including physical/technical reality
5. Balancing items: linked to the choice for fixed variables; either physical/technical reality (accumulations) or economic reality (supply flows).

Interpretation of the results:
When considering possibilities for changing substance flow regimes, two aspects are important: the expected direction and magnitude of the changes in the regional situation, and the problem shifting that may occur. The absolute magnitude of the flows is less important, since no prediction is being made, nor should it be suggested that one is being made. This means that for the interpretation of the results, aggregate indicators can be used for comparative purposes. A confrontation of the environmental flows with NOELs or policy target levels is possible, but can only be interpreted as an indication of the principle sustainability of the regime. The indicator set proposed in Section 4.4 or a selection out of that set can be used to obtain an insight into the overall consequences of a regime change. This borders on the SFA application discussed in Section 5.3.

5.2.5 Predictions: the prediction of a future situation under certain assumptions

A fifth SFA application concerns the prediction of future situations. For environmental policy, an insight into the expected autonomous developments is useful. Policy can then anticipate potentially growing problems and and shift the attention to those rather than addressing problems of diminishing importance. When considering possibilities for abatement measures, predictions of future situations including these measures - alongside the autonomous developments regarding population growth, welfare rise and suchlike - are a useful way to evaluate them. This type of evaluation can be called (or may be part of) a scenario analysis. As stated under 5.2.4, two aspects are relevant for environmental policy: the effectiveness of the measures, and the time it takes for the measures to become effective. In 5.2.4, a way is described to obtain an insight into the effectiveness regardless of the time aspect. In some cases, this will be quite adequate. However, for environmental policy, the time aspect is important. Reduction targets are always set for a specific year in the future, and policy makers are responsible for reaching those targets. Making a reliable prediction, not only regarding substance flows, but more generally, is not easy. It is virtually impossible to come up with something that can be expected to actually happen in all the relevant details. The most that can be hoped for is to sketch a situation that is representative of a future year if all assumptions will prove to be true.

System's definition:
Since the prediction will be linked to environmental policies, the regional approach is indicated. The linkage to policies, especially national policies (since socio-economic predictions mostly refer to the national level), suggests a choice for an administratively defined region. In principle, there is no objection against an environmentally defined system. Both economic and environmental flows are relevant for inclusion. The time will be a specific year in the future, again linked to the reference years defined by environmental policy. If an insight into problem shifting to other areas is desired, an additional system's definition from the functional approach is required.

Quantification of the overview.
When predicting future situations, a high level of accuracy is expected from the model. It must be

possible to compare the predicted situation with the present situation, and to evaluate the impacts of certain developments or policies with regard to set policy targets in a reference year. So far, the predictions that have been made on a national level for emissions and environmental substance flows are mostly based on static modelling, without regard to economic or environmental stocks. An exception to this is the climate modelling including CO, and other climate gases. Often, this static type of modelling is adequate; this is so, for example, in the case of acidifying gases. However, in cases of substances that have a complicated economic life cycle, and especially if they are locked in durable applications, it is not. Delayed impacts and counterproductive impacts may be expected. In these cases, the modelling demands are much stricter. Stocks must be included, since not doing so may lead to highly inaccurate predictions. A dynamic model, i.e. a model wherein time is incorporated as a modelling parameter, is indicated. This leads to the following demands on the quantification procedure:

1. Type of modelling: dynamic model, including the starting situation in the present or recent past according to the bookkeeping overview
2. Fixed variables: the x_n-vector, representing the starting year, contains the fixed variables
3. Stocks: necessarily including stocks
4. Distribution coefficients: economic causality, but including physical/technical reality and also including a time dimension
5. Balancing items: stock changes over the year.

Interpretation of the results:
The interpretation of the results for this SFA application is quite similar to the interpretation of 5.2.1, the evaluation of the current situation, only here it is applied to a future situation. This means that a confrontation between the flows and emissions on one hand and environmental policy targets or NOEL-type information one the other must be possible, and that policy makers should be able to draw conclusions about whether or not the environment is sufficiently clean in their reference year, and whether or not it is being cleaned up according to schedule.

5.3 The overall evaluation of a region's substance chain management regime

An SFA application of a somewhat different type is the use as a screening tool for substance management regimes. A brief characterization of the current, or an alternative, regime on a limited number of criteria can provide a first impression of its consequences for the environment. In Chapter 4, a set of indicators has been proposed for this purpose. These indicators refer to the two aspects of substance management, depletion and pollution, which in combination may refer to the Dutch environmental policy theme of "squandering". It is the actual management that is being pictured: the extent of the losses from the cycle, the amount of recycling that takes place, the amount of virgin input required, and suchlike. The regional situation as well as the three types of problem shifting mentioned before - within the substance chain, to the future, and to other areas - are included in this set. This approach can also be valuable for comparing the substance management regimes of different areas, or for comparing the area's regime with the global "average" regime.

System's definition
For calculating these indicators, an SFA overview of both the regional and the functional approach is required. For most of the indicators, the system can be limited to the economic subsystem.

Quantification of the overview
The indicators are calculated from an SFA overview, regardless of the way this has been achieved. They may refer to the present situation obtained by bookkeeping, to the steady state

belonging to certain regimes, or to a potential future situation calculated by dynamic modelling.

Interpretation of the results
The value of this SFA application is strongly related to the value of the indicators. As stated above, it is a brief characterization of a regime that is obtained, and not information regarding the environmental situation now or in any future. It can be used best for comparison ("while country X has a much higher virgin input *per capita,* its recycling rate is also much higher than that of country Y"). It might be linked to a corresponding system of reference values ("the desired recycling rate for substance Z is 75%"). However, no references exist for any of the indicators at this moment. Currently, the only reference is of the type "less is better", or in the case of recycling "more is better".

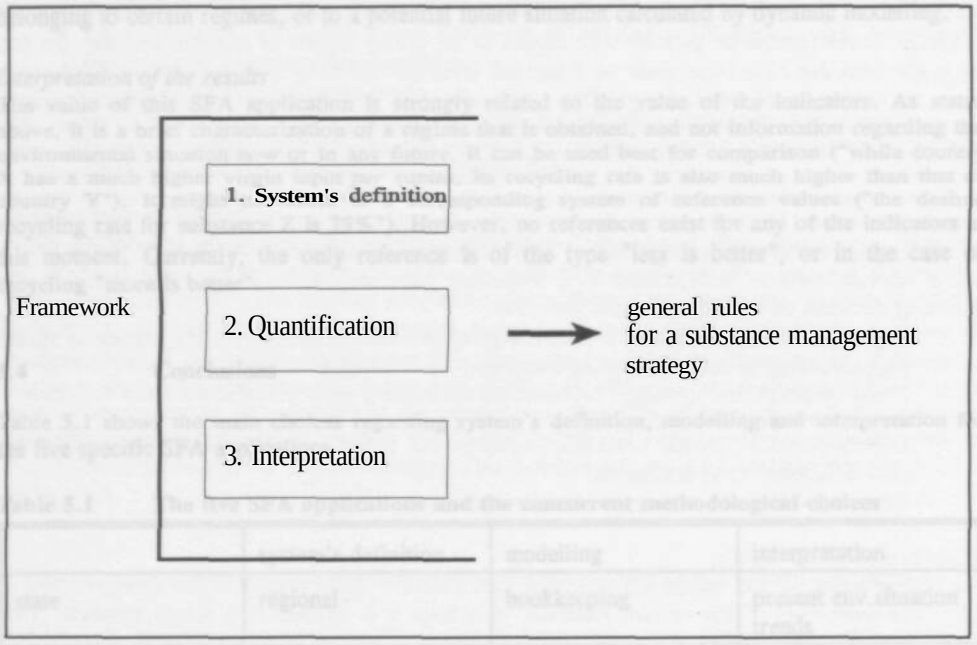
5.4 Conclusions

Table 5.1 shows the main choices regarding system's definition, modelling and interpretation for the five specific SFA applications.

Table **5.1** **The five SFA applications and the concurrent methodological choices**

	system's definition	modelling	interpretation
state	regional	bookkeeping	present env. situation trends
footprint	functional, economic subsystems	bookkeeping	global share pollution export
origins	regional	static modelling physical causality	contribution of sources to problems
solutions	regional (functional)	static modelling economic causality	comparison of regimes
predictions	regional	dynamic modelling economic causality	future environmental situation, predicted developmts

The statement made in Chapter 2, that the methodological choices of the SFA framework must be made differently, depending on the specific SFA application, is given somewhat more perspective in this chapter. For each of the five SFA applications, the system's definition, the appropriate type of modelling, and the required interpretation of the results are specified, and indeed appear to be different for each application. It also appears that within each application there still are a number of choices that can only be made when the goal of the study is defined even more strictly. It is possible that for these, too, guidelines can be formulated. Future research and scientific discussions may enlighten this further.


1. System's definition
Framework
2. Quantification
general rules
for a substance management
strategy
3. Interpretation

CHAPTER 6 ECONOMIC CHARACTERISTICS OF CHEMICALS AS A BASIS FOR POLLUTANTS POLICY[1]

ABSTRACT

The economy-environment relationship, the central issue in the scientific discussions on environmental problems and their solution, can be approached from many angles. In this article, the angle is that of the concept of *industrial metabolism*: the economy-environment analogy on a material level. One of the instruments related to this concept is the study of materials flows in the society's economic system. The approach presented here builds on the results of several materials balance studies. From these studies, it appeared that certain pollution abatement measures are useful for one chemical, but sometimes surprisingly useless or even counterproductive for another. This has led to the idea that, in analogy to the environmental behaviour of substances, a substance-specific *economic behaviour* can be detected. The physical/chemical properties of a chemical, in the context of the surrounding environment, determine its environmental behaviour. In this article, it is argued that the same properties, in the context of the "economic surroundings", are responsible for its economic behaviour. If general rules could thus be discovered for the behaviour of chemicals in the economy, it would then become possible to generate recommendations for the management of such chemicals in a relatively simple way. Apparently strange phenomena then may be explained as a matter of course. Not only the exceptional cases however, but also the 'regular' ones of measures working out as expected - that also might vary per substance - may be captured in those general rules. This would offer less new outcomes for the already existing pollutant management strategics, but it would create possibilities for a profound "streamlining" of pollution policy in general. This article contains a first exploration of this idea by distinguishing a set of *economic characteristics* to explain and predict a substances reaction to certain policy measures.

6.1 Introduction

The economy-environment relationship

Environmental policy is concerned with the (abatement of) environmental problems arising from human economic activities. The central issue in this field, therefore, has been identified as the economy-environment relationship. This issue can be approached from many directions, each approach giving new insights and leading to relevant conclusions of its own. Important questions in scientific discussions on this subject in circles of ecological and environmental economists are, among others, whether there should and can be a 'valuation' of environmental resources, preferably in monetary terms, thereby including the environment as a production factor ("natural capital") and so making it possible to incorporate environmental parameters in economic plans and decisions (Costanza, 1991; Daly, 1980; Odum, 1983). Another approach to the economy-environment relationship is made from a functional angle, connecting environmental parameters to specific economic functions. Instruments for doing so are, for example, Natural Resource Accounting (NRA) - although this concept is not clearly defined and is used in different ways, it boils down to specifying, in very general terms, the goods and services the environment delivers to the society (Odum, 1989; Barbier, 1989); and Product Life Cycle Assessment (LCA) - specifying the integrated environmental impacts of narrowly defined economic functional units (Guinée et al., 1993).

A basic concept in a third direction that has been developed to enlighten the economy-environment relationship is that of *industrial metabolism* as defined by Ayres (1989). This concept argues the analogy between economy and environment on a material level: the economy's "metabolism" in terms of materials mobilization, use and excretion to create "technomass" is compared to the materials use in the biosphere to create biomass. Whereas the biosphere has had millions of years to evolve and attune its processes to such a state that waste generated in one process is converted

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[1] This chapter contains an article published in the *Journal of the International Society for Ecological Economics*. Voet, E. van der, R Kleijn & G Huppes (1995) Economic characteristics of chemicals as a basis for pollutants policy. Ecological Economics 13 (1995) pp 11-26.

into a resource for another, the economy is still in its early stages of wastefulness. In order to speed up the 'economic evolution', society must look at the biosphere for directions. An important investigating instrument in this field is the *materials balance*, a tool for describing the materials regime of economy and environment (applied, for example, by Ayres et al., (1989), Stigliani & Anderberg (1992), and Brunner & Baccini (1992)). This third direction will be taken in this article.

Subject of this article: economic behaviour of chemicals

The main subject of this article is derived from the results of various regional materials balance studies. In these studies, it has been concluded that abatement measures did not result in the expected changes in substance flows, or if they did, they also led unexpectedly to alternative emissions. Rather than dismiss these findings as incidental exceptions, it seemed useful to study this phenomenon more carefully in order to find out whether some general rules may be detected to explain it. The concept of industrial metabolism seems to offer possibilities: in the environment, the behaviour of substances varies according to their environmental characteristics. It may be that an analogy can be found once more. This has led to the main question to be answered in this article: *Would it be possible to expand the analogy between economy and environment, as described in the concept of industrial metabolism, by discovering general rules for the behaviour of chemicals in the economy as we have done for the environment?* If so, it would then become possible to generate rules for the management of such chemicals in a relatively simple way. Apparently strange phenomena then may be explained as a matter of course. Not only the exceptional cases however, but also the 'regular' ones of measures working out as expected - that also might vary per substance - may be captured in those general rules. This would offer less new outcomes for the already existing pollutant management strategies, but it would create possibilities for a profound "streamlining" of pollution policy in general. This article contains a first exploration of this idea.

In section 6.2, cases of the abovementioned unexpected futility of generally useful abatement measures are presented in more detail. In the section 6.3, an attempt is made to explain these facts as a result of substance-related economic behaviour, and a set of *economic characteristics* indicating the response of a substance to certain measures is given. In section 6.4, a tentative protocol is described for the definition of a general materials management strategy based only on economic behaviour. In Sections 6.5 and 6.6, a preliminary application of this protocol is made for two cases of substance management. Section 6.7 contains the conclusions and discussion, and some recommendations for a further research in this direction.

6.2 The ineffectiveness of effective measures

Cadmium - the problem of recycling

Cadmium may lead to health problems mainly through rising concentrations in agricultural systems. Concentrations rise through the mechanism of 'closed loop accumulation', a poisoning of the agricultural cycle by small but constant fresh inputs on a large basic cycle[2]. In the case of cadmium, the fresh input is not even small; concentrations in agricultural soils therefore are rising rapidly. The EC has outlined a cadmium control policy, consisting of end-of-the-pipe emissions abatement as well as source-oriented measures such as a phasing out of certain cadmium applications, and recycling of batteries and possibly other products. The effects of these measures

[2] The phenomenon of 'closed loop accumulation' is one of the subjects of two large-scale studies that will be starting in 1994: a IIASA study on the materials flows of a small selection of metals in various regions of the world, and a study financed by the Dutch NWO on metals flows in the European Union.

on cadmium flows within the EC have been assessed in a materials balance study (Van der Voet et al., 1993). All proposed measures appeared to have side-effects, and even when combined they led to no result. In the case of the end-of-the-pipe measures, the trade-off was most obvious and least harmful: from emissions into air or water, a shifting occurred to larger landfill emissions. The other two measures appeared to work out even less succesfully. Both recycling and a banning of applications lead to a reduced demand for cadmium. Normally, this would result in a reduced supply. For cadmium, this is not the case: supply and demand are virtually unrelated, because cadmium is mined only as a by-product of zinc. The cadmium supply thus is related to the demand for zinc. Recycling, generally accepted as a beneficial measure, leads in the case of cadmium only to a larger availability and consequently to an increase of emissions and/or waste streams with the concurrent environmental problems.

Nitrogen compounds - the inevitability of food production

Environmental problems caused by nitrogen compounds in the EC include acidification (NO_x and NH_3), eutrophication of terrestrial, aquatic and marine ecosystems (all compounds), and global warming (N_2O). These problems are for a large part related to food production and consumption. Measures are formulated to combat these problems in many places and on various scale levels: international (EC and ParCom), national, and subnational (counties and even communities). Measures are invariably directed at small parts of the economic N-cycle, for example: abatement of ammonia emissions from stables, sewage treatment, limits to the application of animal manure and suchlike. In a materials balance study, the nitrogen related problems and the proposed solutions have been analyzed (Van der Voet et al., 1994). It appeared that the measures generally agreed on did contribute to a solution of some N-problems, but also had trade-offs to others. Even a very strict "closing of leaks" scenario appeared not to solve all N-problems adequately: the contamination of groundwater with nitrates cannot at present be solved in a technical manner. Ultimately, the intrinsic inefficiency if agricultural processes, especially those connected to stock breeding, is to blame for this. A source-oriented approach however is no option: we can't do without food. This in short is the basic dilemma for a nitrogen policy: as long as the output of agricultural production in terms of quantity and quality must remain more or less as present, we are faced with the impossibility of a technical closing of the leaks.

Chlorine compounds - a jungle of linked productions

The environmental problems related to organic chlorine compounds are numerous: ozone layer depletion, global warming, toxicity and acidification. Several specific compounds have been or will shortly be phased out (CFCs), for others this option is discussed (solvents, PVC). The opinions on this subject are contradictory and are defended with great zeal. The cohesion between the various economic chlorine chains is large. In many cases, productions are linked, sometimes even within one production process. Measures aimed at one compound are bound to affect a number of others as well. Various studies have been undertaken with respect to economic flows of chlorine compounds, and the possibilities for management strategies (Kleijn et al., 1994). A phasing out of some of the more harmful applications is expected to lead to a production increase of other chlorines on the one hand, especially PVC. On the other hand, some applications are expected to disappear as well because their production processes were too closely linked to the banned ones. Often there is no clarity on which is the main product and which the by-product; changing markets also may change market leaders. This is true even for the basic chlorine production, from which all organic chlorines are derived: chlorine is produced together with caustic soda from common salt, NaCl. When caustic leads the market, chlorine follows and the same disconnection between supply and demand appears as in the case of cadmium. When the roles reverse, chlorine supply and demand are connected once more and the caustic production follows. This makes it extremely difficult if not impossible to predict the effects of any abatement measure and therefore also to generate a management strategy.

Fossil fiiels - abundance as an environmental problem

This example is somewhat different from the others as it does not concern a substance flow problem, but a case of resource availability. Resource depletion generally is included in the list of major environmental problems. In many cases, this is perfectly justified: the disappearance of for example tropical rainforests as a resource would lead to a major environmental collapse. Not only the delivery of "goods", such as wood, medicins, etc., would come to an end but also and more importantly the providing of "services" in sustaining the life support function of the environment. All biotic resources in principle have this double function. This, however, is not the case for geological resources. The disappearance of these resources would lead to problems concerning the "goods" function, but would not affect the "service" function of the environment. Not so much the extraction, but the use of resources such as metals and fossil fuels causes environmental problems: not depletion, but pollution problems. It can be argued that not the scarcity but the abundance of fossil fuels is the environmental problem: as long as we are not forced to consider alternative energy sources seriously, pollution problems remain. Depletion of resources in this case is not an environmental but an economic problem. A straightforward resource conservation policy therefore might postpone a real solution to the problem.

What do these examples have in common?

All these examples of counter-effectiveness of measures and policies can be explained out of the individual characteristics of the substance (group) or resource. For cadmium, the fact that its mining is disconnected from its use was the crucial factor: measures directed at applications or reuse do not prevent its continuing to enter the economic system, and therefore lead to a larger cadmium availability. For nitrogen, the impossibility of conforming to environmental standards is mainly due to the indispensability of nitrogen as a macro-nutrient on the one hand, and the (currently unavoidable) inefficiency of nitrogen use in agricultural processes on the other. For chlorine compounds, the trade-offs occur through confusion by the numerous links and entangled economic processes. In the case of fossil fuels, the inclusion of the depletion problem as an environmental problem leads to potentially contradictory policy goals.

It seems therefore that separate abatement measures work out differently for different substances, depending on the individual characteristics of the substance's pathways in, out or through the economic system. This strongly suggests once again an analogy between economy and environment: in the environment, too, the behaviour varies per substance depending on individual substance characteristics. In the next section, the analogy of substances behaviour in the economy and the environment is stressed, and the concept of economic substance characteristics is explained.

6.3 Statement and elaboration of the central idea: economic substance behaviour

6.3.1 The analogy between the economic and the environmental materials regime

Chemicals and the environment

It is a long standing practice in environmental research to collect data concerning the environmental behaviour of chemicals. The environmental behaviour in fact determines the risks of emissions becoming a hazard for human and environmental health. On the one hand, the dispersal characteristics are important: the ultimate destination of emissions, the accumulation characteristics of the substance in soils and sediments, the tendency to bio-accumulation, the substances persistency in the atmosphere, etc. On the other hand, we want to have information on the hazardous qualities of the substance: toxicity, contribution to the global warming problem,

acidification potential, etc. Based on environmental monitoring and laboratory and field tests, answers have been sought to these questions. Modelling has become increasingly important. Apart from monitoring data, the substances physical/chemical characteristics are an important input for environmental models. For example the Mackay models (Mackay & Clark, 1991) and the QSARs (Hansch, 1971) are based mainly on properties such as lipophility, volatility, half life-times, etc. This is even more true for the problem causing potentials of the substances: for these, measurements such as ODP, GWP and H^+-equivalents have been developed, based almost entirely on the chemicals physical/chemical properties (Houghton, 1991). Environmental factors, such as soil and climate influences but also the current global emission level, have been incorporated in these models as a standardized background. Of course, the validating of the developed models has to take place through specific field or lab measurements. In this way, the environmental characteristics of substances are derived from the physical/chemical properties on the one hand, and environmental and monitoring data on the other hand.

Chemicals and the economy

The subject of this article is to establish an analogy between the society's and the environment's materials household with respect to the determining factors: physical/chemical properties in a (standardized) economic background. At first, however, not the analogy but the major difference between economy and environment leaps to the eye: in principle, materials flows in the economy are controlled not by physical/chemical properties but by man. Two arguments can be brought against discarding the idea too hastily.

First, rather obvious but nonetheless important, materials are used *because* of certain characteristics they have, that make them fit to fulfil specific economic functions. These may be basic functions such as providing food, shelter, clothing etc.; but also very specific functions in products, for example giving a product its colouring, rust protection, impermeability, and so on. In all cases, the substances properties are the underlying motivation for using them. Compounds and materials are even being composed for certain purposes with a specific combination of physical/chemical properties.

In the second place, it is not the controlled flows that are the main cause of environmental problems, but the involuntary ones, eluding human control. From the examples described in section 6.2, it has become apparent that not only the emissions may be regarded as out-of-control, but also in various ways flows and accumulations within the economic system. The involuntary inflow of cadmium, the indispensability of nitrogen and the trade-off mechanisms between the various organochlorines are all examples of rather autonomous mechanisms. These, too, depend on substance characteristics.

These deliberations seem to justify a first, preliminary exploration of the idea. The main question stated in section 6.1 now can be rephrased as follows:

Would it be possible to define a set of "economic characteristics" for a substance that determine the "economic behaviour", in analogy to the environmental characteristics of substances?

Just as the environmental factors have been standardized in order to define environmental substance characteristics, the current economic mode of production could be the standard "background" for the economic characteristics. Whereas the environmental characteristics indicate the need to define an abatement measure policy and will be the starting point for policy **goals** and **standards** regarding environmental quality and emission reduction, the economic characteristics would be the base for formulating a most effective set of policy **measures.**

6.3.2 Economic substance characteristics

A first thinking through of the mechanisms determining the economic behaviour of chemicals leads to a differentiation in three categories of characteristics:

- functional characteristics
- resource and material characteristics
- intentionality characteristics.

These categories are discussed below, including the relation with physical/chemical properties.

Functional characteristics

As stated above, substances are applied in products because they provide certain economic functions, and the fulfilling of these functions is derived from their physical/chemical and biological properties. The intended use of chemicals determine an important part of the economic substance in-, out- and throughput. Ayres et al. (1978) distinguish certain functional characteristics for materials: rigidity, impermeability, strength etc., in order to be able to incorporate the, so far neglected, economic materials and energy use in economic models. These characteristics are important for determining the substitutability of materials in terms, for example, of the cross-elasticity of demand. For substances, such a *substitutability* characteristic, describing whether a substances function could be taken over by another substance, is applicable as well. Another relevant characteristic can be related to the extent to which a function fulfilled by a substance is *dispensable.* In micro-economic terms, this is described in terms of price and income elasticity of demand: a high elasticity classifies a good as a "luxury" while "necessity" goods have a low elasticity (Koutsoyiannis, 1982).

Product-related functional characteristics, such as the durability (Ayres et al. (1978) dichotomize in "durable" vs "consumable" goods), maybe relevant for a substance management as well; however, at present we confine ourselves to substance characteristics.

Resource and materials characteristics

The way a substance enters the economic system and reacts to certain treatments is not only determined by its functional characteristics. In studies on natural resources, a classification according to what might be called economic characteristics is often made in order to establish depletion problems and the possibility for continuing to make use of the resource in the future. It is recognized by economists that these aspects of production and consumption are insufficiently built in general economic models. Since two decades, various attempts and proposals have been made to encorporate the recovery and use of energy and materials in these models (Kneese et al., 1970; Ayres et al., 1978; Folke & Kâberger, 1991). For the purposes of this article, the classification of substances, the relevant economic characteristics are then the *depletability,* determining the chance of resource depletion, the *synthesizability* and *degradability,* indicating the possibilities for replenishing the substance as a resource, and getting rid of it as a waste, and the *renewability* telling us whether the resource in question could be 'harvested' without stock decrease.

The depletability as well as the synthesizability and degradability largely depend on the differentiation between elements and compounds: elements cannot be made, destroyed or depleted in an absolute sense, while compounds can. The depletability of elements in a more practical sense however is not only dependent on the indestructibility of the element, but also on the concentration in which it occurs in its source material, and the abundance and accessability of the source material in the lithosphère. Depletable in an absolute sense are the 'dead' resources such as fossil fuels, originating from living resources but generated only on a geological time scale. Renewable compounds are substances derived from living organisms in the environment. Reproduction adds to the resource, therefore a harvest level might be indicated. The most popular examples are wood and fish, both consisting of organic molecules but with different functions.

Another relevant characteristic related to the substances application is the *concentration:* the ppm amount of the substance in the product. This may be viewed as a characteristic not of the

substance, but of its occurrence in a compound material. The concentration determines waste treatment and emissions control options.

A further important characteristic of a substance is the tendency to involuntary losses during the economic chain. This can be expressed for example in a *waste/emissions ratio*, a ratio between the amount of the material ending up in controlled waste streams and the amount escaping as emissions earlier in the economic life cycle. This waste/emissions ratio depends on substance characteristics on the one hand: volatility, state of aggregation, reactivity. On the other hand, product and process characteristics are important: products intended for dissipative use such as cleaning agents or propellants, whatever chemicals maybe used, will not be found in regulated waste streams, and for example agricultural processes are inevitably less controllable than industrial processes.

Relevant for waste management processes is the *recoverability* of the substance from compound materials. In general, extracting will be possible for elements but difficult or impossible for compounds.

Intentionality characteristics

The abovementioned characteristics determine the 'ordinary' economic life cycle of a substance: its entering the economic system as a resource, its application in products, and its leaving the system either as waste or as an emission. The ordinary route may be seriously complicated, however, by the factor of non-intentionality, marring the normal relations between recovery or formation, applications, and economic functions. In the example of cadmium, the non-intentional recovery appeared to cause its unruly behaviour. The *non-intentionality of recovery* is important for all substances recovered mostly or entirely as ore contaminants. A chemical likeness to the main ore might be identified as the underlying physical/chemical property. For compounds, the *non-intentionality of formation* is the analogous characteristic. Dioxins, PAH and NO_x are examples of chemicals with an entirely non-intentional formation, due to the presence of certain basic elements, catalysts and process circumstances. Less extreme examples can be found in the chlorine industry, where the production of one compound automatically involves the production of another as a co- or by-product. For many more substances, not only the economic inflow but also the economic application is non-intentional. Because cadmium occurs as a contaminant in phosphate rock, it is also a contaminant in phosphate fertilizer. Once a substance occurs in a product as a product contaminant, its economic life cycle is further determined by that product. This *non-intentionality of use* automatically implies that the "application" does not fulfil any economic function. The occurrence of trace pollutants is very common in secondary materials such as fly ash, slag, compost or manure. The chance of ending up in secondary materials can be traced back to the substances persistency as an important physical/chemical property. The use of these materials in building or agriculture may easily lead to closed loop accumulation. This third category of characteristics are least generally accepted. Whereas joint production is part of economic theory and modelling, the involuntary generation of pollutants and the "application" of a substance as a trace contaminant are not.

In Table 6.1, the economic characteristics distinguished in the above are summarized.

Table 6.1 Economie substance characteristics categorized in three groups.

functional characteristics	resource and material charact.	intentionality characteristics
substitutability	depletability	intentionality of recovery
dispensability	renewability	intentionality of formation
	synthesizability	intentionality of use
	concentration	
	recoverability	
	waste/emissions ratio	
	degradability	

6.4 A protocol for formulating a general substance management strategy based on economic characteristics

The general approach, also taken in the test-cases, can be described as a five step plan:

1. define substance/group of substances involved and determine appropriate level for application of measures
2. determine economic characteristics from basic data concerning substance properties and applications
3. determine main management target(s) from economic characteristics
4. confront general abatement options with the economic characteristics
5. compose basic management strategy out of the useful options

Ad 1. A first task is to determine what exactly we mean by "substance", or in other words which elements and compounds are relevant. For example, if we speak of "chlorine" we generally implicitly exclude NaCl, because we really mean "hazardous chlorine compounds" or sometimes even only "hazardous organic chlorine compounds". To determine which compounds are relevant, the environmental problem causing potential is important: a high potential indicates that the substance must be included. The cohesion of economic chains, from inflow to outflow, is another important element: substances which are harmless in themselves can be transformed in economic processes into hazardous ones.

Secondly, a decision must be made to which level a comprehensive policy, encompassing all selected substances, must apply. In general, measures can apply to a substance at four different levels:

- the element level (Cl)
- the molecular or compound level (CFC-11, dichloroethane, 1,2,7,8-TCDD)
- the materials level (PVC plastics)
- the product level (packaging, solvents, carpets, hair spray).

Which level is indicated, depends on the substance in question. In most cases, a policy will be directed at all four levels. However the main focus in a substance policy will generally be on the element and compound levels.

To complete this first step, information is needed with regard to the economic applications of the substance or substance groups, and the way these are connected. In short, a flow chart (that does not have to be quantified) of the important economic flows is required.

Ad 2. With regard to the environmental characteristics, lists are available wherein a score is added to each substance (ODP, GWP, toxic properties etc.) (for example, the classification factors used in product Life Cycle Assessment studies as listed in Heijungs et al., (1992)). For the economic characteristics no such lists are available, but would have to be composed out of

physical/chemical, biological, and geological properties on the one hand, and data on the economic applications on the other hand. In the next section, a rough attempt is made in the examples, scoring only + or - on the economic characteristics. This oversimplification - a substance is seldom entirely substitutable, or not at all, but to some extent and in some applications - is made to get a quick first impression of the usefulness of the approach in principle.

Ad 3. In general, the two main targets of a substance management are pollution prevention and resource conservation. The relevance of either or both depends on the substance in question. Depending on the substance and the situation, more specific goals may be identified. This will not be attempted in this article.

Ad 4. A not too large number of general options for a problem abatement strategy can be identified:

1. prevention of recovery or formation
2. extraction of pollutants from the main material
3. closing process leaks in a technical sense (including increasing process efficiency)
4. terminating use or application (if necessary including substitution by another substance)
5. recycling a: collection and product re-use (depending on product, not substance characteristics)
6. recycling b: collection, substance recovery and substance re-use
7. recycling c: re-use of products of waste management processes (compost, fly ash, sludge etc.)
8. waste management a: collection and landfill
9. waste management b: collection and degradation (possibly but not only by incineration)
10. waste management c: collection (extraction) and immobilization.

Again, these options are formulated in an absolute sense. In practice, "prevention" or "termination" will be at most a "limiting" of application or recovery. Again, the oversimplification is made for arguments sake. The specific combination of economic characteristics for a substance or group of substances deliver a specific combination of measures that are possible (useful) in principle, as will be tried to establish in the next section.

Ad 5. After step 3 and 4, the selected options must be combined to a comprehensive strategy. In the process, attention must be given to the connection between the separate parts. Most important here is to avoid the inclusion of contradictory options, and to include all stages of the substances life cycle.

In the next section, the general approach is roughly applied in two cases: cadmium and nitrogen compounds. The economic characteristics of these substances are determined and recommendations for a general substance management are derived from them. No attention is being paid to the environmental side; the need for emissions abatement is being taken for granted. The situation in Western Europe and more specific the EC forms the environmental and economic background.

6.5 Application of the protocol: the case of cadmium

Cadmium (Cd) is applied in different forms. Most important are:

- metallic cadmium, in alloys, coatings, batteries and several others
- CdO and $Cd(OH)_2$, mostly as an industrial intermediate for other Cd-compounds
- CdS, in pigments
- Cd-salts of organic acids, or in organic molecules, as stabilizers esp. in PVC.

Less bulky applications exist of other Cd-compounds, mostly simple salts. Cadmium also occurs

as a contaminant in products from metal ores (zinc, iron), from fossil fuels and from phosphate rock.

Cadmium is extracted from the lithosphère only as a by-product of other metals ores, especially zinc, and as a contaminant in fossil fuels and phosphate rock. Cadmium is a relatively scarce element in the lithosphere (World Resources Institute, 1990). It has the physical/chemical properties of a metal: solid, good conductor, etc. Its metal structure shows a great similarity to that of zinc, probably the reason of its occurring as a standard zinc ore contaminant. Contrary to most metals, cadmium is bio-accumulative, especially in animal tissue. It does make little difference in what compound Cd is emitted to the environment; the harmful effects are due to the element Cd. All intentional cadmium applications ultimately are derived from metallic Cd extracted from zinc ores, and can be degraded again to metallic Cd. In all cases except NiCad-batteries, Cd is applied in low concentrations (stabilizers, pigments, coatings). In most cases, the function Cd performs in a product is not vital, or can be taken over quite easily by other substances.

Step 1: Relevant forms of cadmium
Important forms of Cd to be included are in the first place the sources: cadmium containing ores, and fossil fuels. Important forms of Cd circulating in the economic system are: metallic Cd, the simple Cd-salts, and finally Cd as a trace contaminant. A cadmium management must encompass all mentioned Cd-compounds. Since all are derived from the same basic resource, the focus is on the element level.

Step 2: Economic characteristics of cadmium
In Table 6.2, the economic characteristics of cadmium in its various relevant forms is scored.

Table 6.2 Economic characteristics of cadmium.

	sources		*ec. rel. forms*		
	ores	fossil Cd	Cd-metal	Cd salts	Cd as trace pollutant
functional					
dispensability			+	+	
substitutability			+	+	
resource/materials					
depletability	+	+			
renewability	-	-			
synthesizability/degradability		-	-[1]	-	
recoverability			+	+	+
concentration			+/-	-	-
waste/emissions	ratio		+	+	-
intentionality					
intentionality of recovery	-	-			
intentionality of formation					
intentionality of use			+	+	-

[1]Only degradable to metallic cadmium

Step 3: Main management targets
For a cadmium management, the prevention of pollution is the main target. Although Cd scores

high on depletability, resource conservation is only of secondary importance because of the high scores on dispensability/substitutability.

Step 4: Economic characteristics and general abatement options
A first scanning of the principle options from section 6.4 leads to the following list:
prevention of recovery:

Prevention of mining is difficult for cadmium because of the low intentionality score, unless directed at the main materials: zinc, phosphate, and fossil fuels. Prevention of recovery from the zinc ore is possible, but would lead to a higher cadmium concentration in zinc applications with concurrent corrosion emissions, and probably to a transgression of EC product standards.

extracting Cd from the main material:

Extraction of Cd from Zn ore and from phosphate rock is applied already in practice. The often low concentration however leads to expect that technical limits are reached rather soon.

closing of leaks:

For industrial processes, this is to a large extent possible as is indicated by the high waste/emissions ratio. In fact such a reduction has been applied and has led to a major reduction of industrial emissions in the EC over the last 20 years. Special attention is required for waste incineration: the temperatures frequently rise to above the boiling point of cadmium. Most problematical are the non-intentional applications, especially in agriculture.

terminating of applications:

For the intentional Cd-applications, this is to a large extent possible due to the high substitutability/dispensability score. For non-intentional uses (as a product contaminant) this is not applicable. Because of the non intentionality of recovery, this measure is - although possible - useless even for the intentional applications, unless it is linked to an adequate prevention of recovery of the main material (zinc, in this case), or a sound management of the alternative waste stream (jarosite).

recycling b (extraction and substance recycling):

Possibilities for separate collection of cadmium containing products are limited to the intentional uses. Recovery of Cd is often possible, but technical limits are expected to be reached soon in low concentration applications. NiCad batteries offer the best possibilities; extraction of Cd applied as pigment, stabilizers or coatings is at this moment not possible.

recycling c (waste management products):

Use of cadmium containing fly ash or compost is undesirable from the point of view of a cadmium management: cadmium, due to its non-degradability, ends up as a contaminant in these materials and using them could cause closed loop accumulation.

landfill:

Landfill naturally is possible for all cadmium applications, with the concurrent risk of dispersal from the site.

waste degradation:

This measure is not applicable for the non-degradable element Cd.

waste immobilization:

The limits for this option depend on the availability of immobilizing techniques. For heavy metals such as cadmium, such techniques are hardly available at present, but are imaginable in two directions: locking cadmium in low concentrations in "glazed" slag, or concentrating it in order to put it into permanent or at least long term storage.

Step 5: Cadmium management outline
This leads to the following outline for a general cadmium management:

1. The prevention of cadmium mining is desirable in two ways: as a depletion alleviating measure, and as a necessary step for emissions prevention. This is possible only through measures directed at zinc, phosphate and fossil fuels.
2. Technical prevention of emissions to air and water is desirable; much has been achieved already but more can be done.
3. Low concentration applications tend to escape from control. In so far these are intentional applications, they can be limited to a large extent.
4. This terminating must be linked to either a prevention of recovery directed at the main materials or to a sound management of the generated Cd-waste, in order to prevent alternative emissions.
5. Non-intentional applications can only be prevented by directing attention at the main materials (low cadmium ores, for example). If this is not possible, extraction of cadmium from the main material is indicated.
6. High concentration applications can be collected and the Cd can be extracted.
7. Recycling of the extracted Cd is useful only if linked to a reduced recovery. In the case of cadmium, this linkage is not automatic (see 1).
8. Reduction of cadmium mining is dependent on the reduction possibilities for the main materials. If these are not sufficient from a cadmium point of view, which will to all probability be the case, immobilization of Cd-waste is the indicated route. The attention therefore must be directed at developing waste treatment techniques in this direction. A back-link to solving the depletion problem can even be imagined by considering the immobilized cadmium as a potential future resource.

This outline contains most of the measures from the EC proposed policy. Additional measures are those included to avoid side-effects: the explicit feedback to the recovery of the main materials, the recognition of the immobilization route as the indicated waste treatment option, and the suggested "storing for the future" (measures 1, 4, 5, and 8). The economic characteristics have proved a valuable starting point in the case of cadmium.

6.6 Application of the protocol: the case of nitrogen compounds

Nitrogen is an abundant element, both in the environment and in the economy. Most important economic forms are:
- N_2: basic resource for most industrial N-applications; application as liquid in industrial processes in modest amounts
- NH_3: directly derived from N_2; main precursor for industrial applications, especially fertilizer
- NH_4-compounds: most important application in fertilizers; in small quantities in cleaning agents and others
- NO_3- and NO_2-compounds: most important application in fertilizers; in smaller quantities in industrial processes as nitric acid, in explosives etc.
- organic molecules produced in the chemical industry: in plastics, synthetic fibres, detergents, pesticides, pharmaceutical products etc. etc.
- organic molecules from agricultural and biological origins: as a macronutrient in food products, in organic fertilizers, and in products from biological origins such as wood and paper
- as a contaminant in fossil fuels.

The inflow of nitrogen (compounds) in the economic system takes place in three different ways: through fixation of atmospheric N_2 in industrial processes, by recovery of fossil fuels, and by "harvesting" from biological sources. The industrial fixation is by far the most important of the three. Industrial as well as agricultural applications ultimately originate from this source.

Moreover, NO, is involuntarily formed out of N_2 in combustion processes. N_2, an inert gas, is abundantly present: 80% of the earths atmosphere is nitrogen gas. The inorganic compounds are gases (NH_3 and NO_x), salts (nitrates or ammonium compounds), or solutions (both acids and bases); in the organic compounds N is present in proteins. All compounds are easily degradable to N_2. At this moment, environmental problems related to N-compounds are mainly connected to agricultural processes. Large amounts of nitrogen are lost in these processes; currently only 12% of the applied N ends up in food products in the EC situation.

Step 1: Relevant forms of nitrogen
From the point of view of relevancy, the basic resources N_2, fossil fuels and organic N-compounds extracted from the environment must be included, as well as the important nitrogen forms in the economy NH_3, NO_x, the salts and acids, and the organic N-compounds related to agriculture. Although the environmental impacts of the various N-compounds vary greatly, the economic chains and cycles are strongly interconnected. This would be an argument in favour of a management on the elemental level. On the other hand, there is no need to regulate the main resource N_2, as it is abundantly available and environmentally completely harmless. The choice is made, then, for encompassing all N-compounds in a comprehensive strategy excluding N_2.

Step 2: Economic characteristics of nitrogen in its various compounds
In Table 6.3, the economic characteristics of the relevant N-compounds are summarized.

Table 6.3 Economic characteristics of nitrogen compounds.

	sources			*ec.rtl.forms*				
	N_2	fossil N	org. N (envir.)	NO_x & trace	NH,	N-sol. & salts	org. N (agr.)	org. N (env.)
functional								
dispensability				+	-	-	-	-
substitutability								+
resource/materials								
depletability		+	+					
renewability			+					
synthesizability/degradability				+	+	+	+	+
recoverability					-	-	-	-
concentration	+					+	+/-[1]	[2]
waste/emissions ratio						+	-	-	+
intentionality								
intentionality of recovery	+		+					
intentionality of formation					-	+	+	+	
intentionality of use	(+)[3]					+	+	+	+

[1] Concentration is high in fertilizer applications, lower in others.
[2] The concentration of N as an element in the molecules is low, but the concentration of N-containing molecules in the tissue is high.
[3] The economic use of nitrogen as N_2 is limited and does not involve other N-compounds. It is not included in the table under the economically relevant forms although strictly speaking it should be.

Step 3: Main management targets
For nitrogen, resource depletion is no problem and therefore resource conservation has no priority. A nitrogen compounds management therefore should concentrate on alleviating pollution problems.

Step 4: Economic characteristics and abatement options

prevention of recovery/formation:

For the intentional recovered/synthesized compounds, this is of course eminently possible. For the non-intentional recovery/formation prevention is only possible by preventing the recovery of fossil fuels and change the process circumstances of NO_x-generating processes.

extraction from main material:

Only **relevant for nitrogen as a trace pollutant in fossil fuels; not applicable because of low** extractability.

closing of leaks:

The leaks in the economic nitrogen cycle are huge and closing them would be desirable indeed. For the intentionally formed or recovered N-compounds, this would automatically imply a diminished inflow. For some emissions, especially NO_x, technical emission reduction is the only solution. However the possibilities for closing cycles in agriculture are at present not overwhelmingly large. Technical emission reduction has limited results and an increase of the agricultural efficiency can only be expected in case of a strong decrease of animal production.

terminating of applications:

For the major part of N-compounds, all those that are related to the food production and consumption cycle, terminating is not applicable because of indispensability. One food product may be substituted for another, but the human N-need remains.

recycling of the element N:

Not applicable because of low recoverability.

recycling of waste products:

For nitrogen compounds, the use of secondary materials is practised on a large scale at this moment (manure, compost, sludge). This might be enhanced further. Process leaks are problematical (see "closing of leaks") but the alternative waste management would be problematical as well because of the huge amount of waste materials.

landfill:

Landfill is always possible, with the concurrent risk of leaks to the environment.

waste degradation:

Because of the high degradability this is a good possibility. Chemical and biological denitrification processes are in this case more recommendable than incineration because of the risk of generating NO_x-compounds.

waste immobilization:

This option seems far less appealing than waste management b and might not be possible due to the high degradability and mobility of the derivatives.

Step 5: Nitrogen compounds management outline

From the results of step 4 the following recommendations can be formulated:

1. The NO_x problems seem to be largely disconnected from the other N-related problems with regard to the economic origins. Moreover, the NO_x economic life cycle is entirely non-intentional. Prevention of inflow therefore is indicated. A NO_x-management must concentrate on a diminished recovery of the main material, in this case fossil fuels, and on controlling the combustion processes that generate NO_x.
2. All other compounds are recovered or synthesized as well as used intentionally, which means that measures directed at any part in the economic chain automatically affect the whole chain.
3. For the N-compounds recovered from a renewable resource, such as wood and fish, no specific N-policy is required. For the other compounds, depletion of resources is no problem. Recycling has no priority from that point of view.

4. As only a minor amount of the N-compounds applications are substitutable or dispensable, terminating of applications is no viable option. The only route for prevention of emissions appears to be the closing of process leaks, by end-of-the-pipe means or by increasing process efficiency.
5. The bulk of N-compounds is used in agriculture, with its inherent inefficiency of processes and concurrent large losses to the environment. Closing of leaks therefore is, however necessary, extremely difficult. This in short characterizes the basic dilemma when formulating an adequate N-management strategy.
6. In theory, there are several ways to increase the efficiency. Since a substantial emission reduction is required in the EC, the options must be rather drastic. A first possibility is the industrialization of agriculture - large scale use of greenhouses with nutrient recycling, application of central manure treatment on a large scale and suchlike. A second direction is a production decrease to a level that allows the concurrent leaks to be below environmentally acceptable levels. A third equally drastic possibility is a substantial decrease of animal production as by far the most inefficient step in the agricultural system. None of those are viable options at this moment; this implies that problems related to losses of N-compounds from the food providing and consuming sectors inevitably remain partly unsolved for the present.
7. Collection and degradation seems the indicated waste treatment option for N-compounds. The degrading process may best be directed at denitrification, converting all N-compounds to harmless atmospheric N_2. Reuse of N-waste as compost can be viewed as another possibility, however, again leading to leaks to the environment.

To the fragmentary, detailistic and sometimes contradictory N-management measures and plans formulated on the various administrative levels, this approach has at least added one thing: a comprehensive overview. New is also the realization that nothing short of an agricultural revolution will enable us to conform to environmental quality standards (at least in the EC), due to the main N-dilemma of the need for and the impossibility of closing process leaks. On the level of the actual measures proposed, little can be concluded as to what's new: there is too much discrepancy in the levels of thinking. It may be expected that, as with cadmium, most measures out of the existing packages will turn out to be useful if applied in their proper place, as a part of an encompassing strategy.

6.7 Conclusions, discussion and recommendations for further investigation

The tentative answer to the main question as stated in section 6.3.2, 'would it be possible to define a set of "economic characteristics" for a substance that determine the "economic behaviour", in analogy to the environmental characteristics of substances', is affirmative. It appears that economic characteristics can be formulated, based on physical/chemical and other substance properties on the one hand and on data related to the economic applications on the other hand. Also, it appears that these economic characteristics can be used to draw conclusions regarding the principle usefulness of general abatement measures in each specific case. A protocol as outlined in Section 6.4 and applied in Sections 6.5 and 6.6 could be used to obtain a first rough draft for any specific pollutants policy. Further investigations on this subject seem justified in the light of a potential substantial streamlining of pollutants policy.

The general management strategy outlines for cadmium and nitrogen compounds are sketchy. However, the general outlines have the distinct advantage of being comprehensive (including all stages of the economic life cycle), and appear to be avoiding more and less obvious mechanisms of problem shifting. On a general level, they make sense and therefore may serve as guidelines for a more detailed substance management measure package. It has proven possible, therefore, to make the connection between general, easily available substance data and the main directions for

its management. In order to translate the outlines into a real management strategy, more information is needed: a quantification as well as a qualification of the economic life cycle, an inventory of existing abatement techniques, and an estimate of the effectiveness of the various techniques and of the alternative waste streams that are generated. For the cases in section 6.4, these data were available from prior materials balance studies. Although these data have not been used directly, the knowledge no doubt has influenced especially the management outlines. A further test could be to conduct the same exercition for a substance without prior knowledge.

An obvious first step on the way to operationalization is to seek the opinions from other researchers in this field, both economists and environmentalists, on the viability of the approach. This may help to clarify the ideas and detect the flaws. A next step would be the definition and demarcation of the various parts:

- the definition of a useful and complete set of mutually exclusive economic characteristics related to the economic system in terms of in-, out- and throughflows of materials
- the specification of the data that will be needed in order to derive a substances economic characteristics
- the development of procedures to use the economic characteristics in the formulating of a materials management (in this article, the five-step protocol)
- the proper place of the protocol in the field of pollutants policy, product policy, process policy, resource policy etc.

Eventually, if more insight is gained in the possibilities and limitations of the approach, some fundamental research may be conducted. Translating the economic characteristics into problem causing potentials (again in analogy to the environmental problem potentials) is one possibility; conducting measurements, for example on waste/emissions ratios for substance life cycles, might be another.

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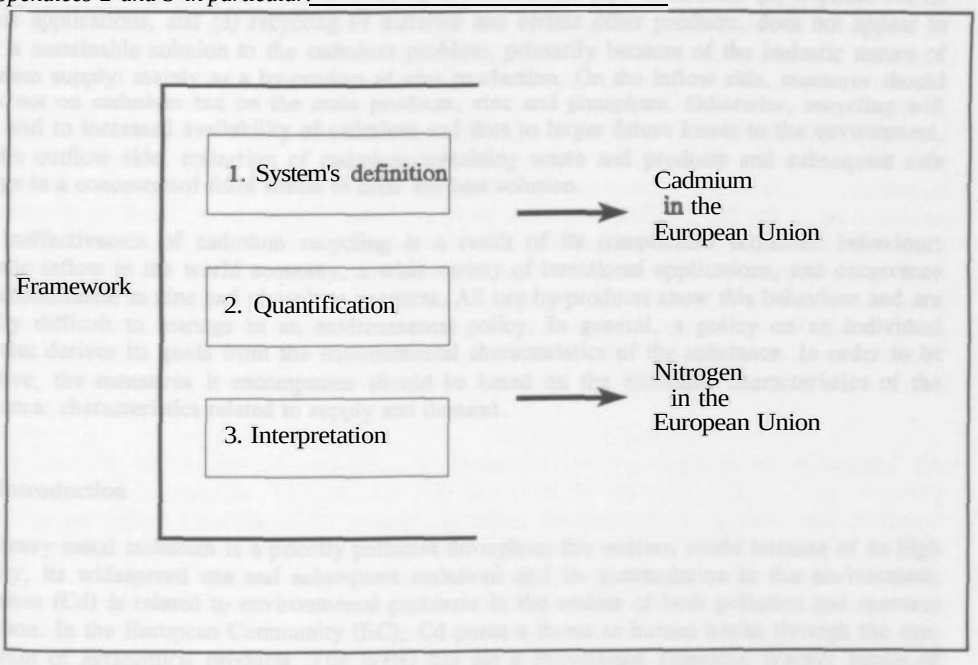
PART IV CASE STUDIES

In Pan IV, the SFA method is being applied in two case studies: cadmium and nitrogen compounds, both for the European Union.

Chapter 7 contains the cadmium case study. This chapter has been published as an article in the journal Waste Management and Research. Chapter 8 contains the nitrogen case study. This text has been sumitted as two separate articles to the journal Environmental Conservation. The first one, paragraph 8.1 in this text, has been accepted pending minor revisions. In Chapter 9, both case studies are evaluated with regard to data quality and modelling choices. All three appendices belong to Part TV. All three refer to the evaluation of case studies: appendix 1 in general, and appendices 2 and 3 in particular.



The cadmium pollution problems can be traced back to two major sources: phosphate rock and zinc ore. Almost 70% of the 1987 inflow of cadmium appears to accumulate in the economic system. This stockbuilding indicates a risk for a future increase in emissions. The generally accepted notions of source-oriented policy and recycling do not appear to work in the case of cadmium. This is caused by the inelastic nature of the cadmium supply, because of which a diminished demand does not lead to a decreased supply. A cadmium policy therefore should address the ultimate sources on the one hand, and concentrate on waste immobilization on the other.

Differen nitrogen related environmental problems in the EU can be traced back to a single most important source: the industrial N_2 fixation for the production of fertilizer. Neither the agricultural overproduction in the EU, nor the import of fodder appear to be important causes of the N-related problems. The solution of all N-problems and the current EC agricultural production appear to be incompatible, even when a maximum package of technical abatement measures is presupposed. Either very drastic changes are required in both food production and consumption, or the environmental targets must be set less strictly.

CHAPTER 7 CADMIUM IN THE EUROPEAN COMMUNITY: A POLICY-ORIENTED ANALYSIS[1]

ABSTRACT

The economic production and use of cadmium leads to environmental problems within the EC. The use of cadmium is still increasing significantly, mainly in batteries. This article presents an analysis of cadmium flows in the economy and the environment of the EC, using the 'Substance Flow Analysis' method, a variant of the materials balance approach. Several cadmium abatement packages are evaluated for their effectiveness in terms of sustainability.

Proposed EC policy on cadmium, embodying (1) end-of-the-pipe measures, (2) a phase-out of certain applications, and (3) recycling of batteries and certain other products, does not appear to offer a sustainable solution to the cadmium problem, primarily because of the inelastic nature of cadmium supply: mainly as a by-product of zinc production. On the inflow side, measures should focus not on cadmium but on the main products, zinc and phosphate. Otherwise, recycling will only lead to increased availability of cadmium and thus to larger future losses to the environment. On the outflow side, collection of cadmium-containing waste and products and subsequent safe storage in a concentrated form seems to offer the best solution.

The ineffectiveness of cadmium recycling is a result of its complicated economic behaviour: inelastic inflow in the world economy, a wide variety of intentional applications, and occurrence as a contaminant in zinc and phosphate products. All ore by-products show this behaviour and are equally difficult to manage in an environmental policy. In general, a policy on an individual pollutant derives its goals from the environmental characteristics of the substance. In order to be effective, the measures it encompasses should be based on the economic characteristics of the substance: characteristics related to supply and demand.

7.1 Introduction

The heavy metal cadmium is a priority pollutant throughout the western world because of its high toxicity, its widespread use and subsequent emissions and its accumulation in the environment. Cadmium (Cd) is related to environmental problems in the realms of both pollution and resource depletion. In the European Community (EC), Cd poses a threat to human health through the consumption of agricultural products. The WHO has set a Provisional Tolerable Weekly Intake of 0.4-0.5 mg Cd, based on a maximum load of 1 μg Cd/kg body weight (JECFA, 1989). The average intake level in the EC around 1980 was estimated at 0.25 mg Cd/week (Hutton, 1982a). In The Netherlands, the tolerable intake level is almost reached just through ordinary food consumption (JECFA, 1989; Ros & Slooff, 1987). Other investigations show that the Cd content °f Dutch bread, prepared chiefly using wheat from outside the Netherlands, in many cases equals the standard (Konsumentenkontakt, 1991). Hence it is to be expected that in other parts of the EC, too, Cd pollution constitutes a threat to public health. In addition, aquatic ecosystems in several European countries are threatened by pollution with Cd (and other metals) (CCRX, 1985). Throughout the EC, there are local problems involving Cd dispersion from large dump sites (RIMH Noord-Brabant, 1987; RIVM, 1992).

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[1] This chapter contains an article published in *Waste Management & Research*: Voet, E. van der, L. van Egmand, R. Kleijn & G. Huppcs; Cadmium in the European Community: a policy oriented analysis. WMR (1994) 12, pp 507-526.

On the other hand, there is a depletion problem. Known resources of zinc, the main source of Cd, currently stand at only 21 years (World Resources 1990-1991, 1992). However, the true gravity of this problem is not entirely clear: in most applications, Cd can more or less readily be replaced by other substances, and with the discovery of new stocks the 'life expectancy' of zinc increases every year. A sustainable Cd management regime must take into account both pollution and depletion problems, such as they are.

Cadmium is a component of several (raw) materials and products, either through intentional application or natural occurrence. The most important source of metallic Cd is zinc ore, from which it is extracted during zinc refinement.

Metallic Cd is used for its resistance to corrosion, its stability under high temperatures and sunlight, the striking colours of its salts and the fact that it makes excellent electrical contacts. It is used industrially in a wide range of applications including pigments, stabilizers for plastics, alloys, plating and, last but not least, rechargeable batteries. This last application has become increasingly important in recent years (Cadmium Association, 1988).

Besides zinc ore, several other raw materials also contain relatively high percentages of Cd (Ros & Slooff, 1987). The most important are phosphate rock and limestone, but iron ore, copper ore, lead ore, crude oil and hard coal also contain Cd as a contaminant.

In this paper, a materials balance approach is used to analyze Cd flows through the economy and environment of the EC (Section 7.3). The purpose of this analysis is to link the environmental problems related to Cd (as described in Section 7.2) to their economic origins. From the' analysis, some general principles are deduced regarding the effectiveness of Cd abatement measures. Measures under the EC's outline Cd policy are evaluated for their environmental effectiveness and possible side-effects. Additionally, some alternative measures are suggested and their effectiveness likewise assessed (Section 7.4). Finally, some generalizations are made (Section 7.5) and conclusions drawn (Section 7.6).

7.2 Effects of cadmium

Cadmium has a strong bio-accumulative tendency. Because of its chemical similarities to zinc, a nutrient, it is absorbed in human, plant and animal tissues quite easily. Eventually, this may lead to disease or even mortality through a building up of cadmium concentrations.

Humans can ingest Cd through the lungs and the digestive tract. Cd uptake is determined by the ingestion route: in the case of inhalation, fifty percent of the Cd is retained; in the case of digestion, only five percent (Elinder, 1982). The most important sources of Cd exposure are food consumption and tobacco smoking. The effects of Cd depend on the duration of exposure and on the exposed species. Long-term exposure to low doses can lead to malfunctions of liver, kidney and lungs, the organs in which Cd most readily accumulates. Exposure to high doses of Cd disturbs calcium metabolism in the body. In combination with low calcium and vitamin D intake, this can result in décalcification of the bones (osteomalacia), affecting elder women in particular. In the fifties this occurred in a number of locations in Japan (Itai-Itai disease), where consumption of contaminated rice and drinking water led to high Cd exposure (Friberg et al., 1974). Cd exposure may also have other detrimental effects, such as cancer and hypertension, but this has never been proved decisively.

Cadmium also affects natural ecosystems. In aquatic ecosystems, the effects are dependent on salinity. In freshwater ecosystems, low Cd doses (0.1 mg/l) can be lethal for many fish and crustacean species (CCRX, 1985). This may lead to disturbance of the whole ecosystem, since these

species are consumed in turn by other organisms. Saltwater ecosystems are less sensitive to Cd pollution: the concentration at which (sub)lethal effects occur is approximately ten times higher (CCRX, 1985). The effects of Cd in terrestrial ecosystems are largely dependent on the type of soil, since biological availability is influenced by such soil characteristics as pH (Chardon, 1985). Cd uptake in plants takes place through the root system and leaves. Susceptibility to Cd poisoning is highly dependent on plant species (Commission of the EC, 1983).

In the next section, cadmium-related environmental problems are traced back to their origins.

7.3 Analysis of cadmium flows in the economy and environment of the European Community

7.3.1 The substance flow analysis (SFA) method

For the analysis of cadmium flows in the EC, a materials balance method has been adopted. A summary of the analysis is given in Figure 7.1: the Substance Flow Diagram (SFD, first published by Udo de Haes et al., 1989). Data from a great many sources have been used to complete this picture[2].

Figure 7.1 shows cadmium flows and changes in stocks in the EC. In the following section the underlying processes are described, distinguishing between economic and environmental processes.

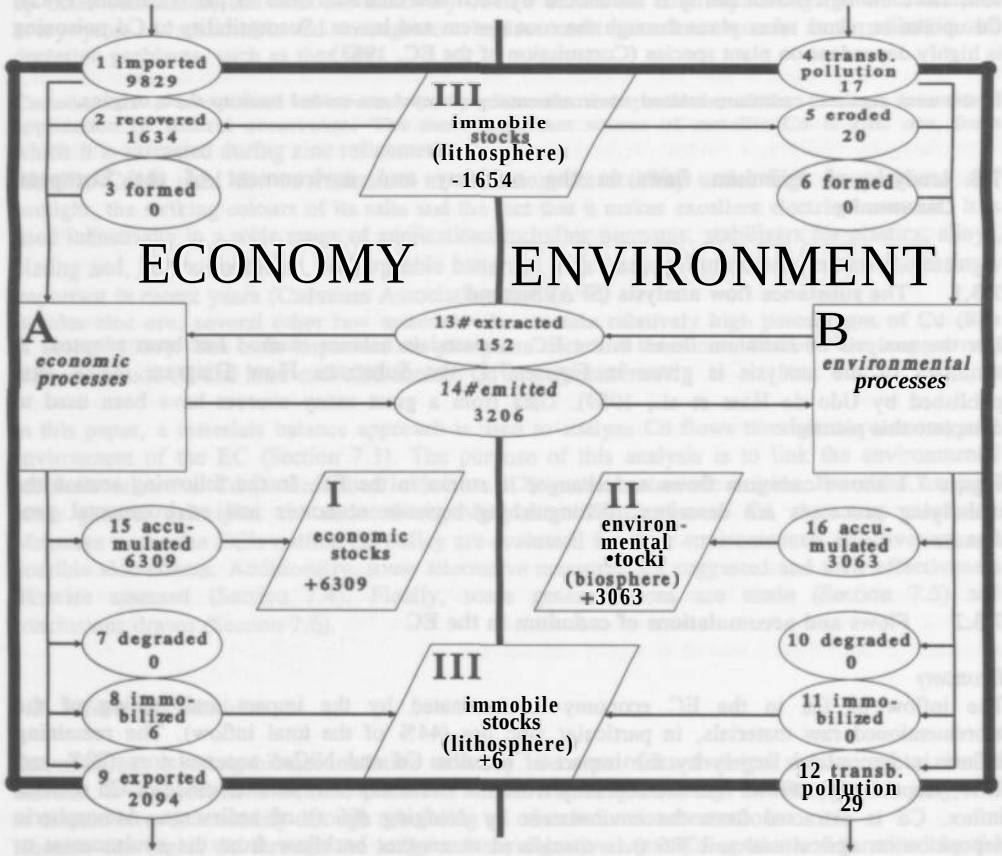
7.3.2 Flows and accumulations of cadmium in the EC

Economy

The inflow of Cd in the EC economy is dominated by the import and mining of the aforementioned raw materials, in particular zinc ore (44% of the total inflow). The remaining inflow is determined largely by the import of metallic Cd and NiCad accumulators (20% and 19%, respectively). Flows into the economy from the environment is another mode of Cd societal influx. Cd is extracted from the environment by dredging (66 t) of sediments. Atmospheric deposition on agricultural soil (86 t) is considered as another backflow from the environment to the economy (agricultural soil being defined as a part of the economy). Cd flows out of the economy through export of metallic Cd (15%) and of materials and products in which Cd is intentionally used, e.g. pigments (22%), plastics (20%) and NiCad batteries (15%). The flows to the environment (or in other words, the emissions) constitute the largest economic outflow. The inflow total, however, is much larger than the outflow total, resulting in a strikingly large economic accumulation: more than twice the level of environmental accumulation. In 1987, a total of 6309 tonnes of Cd accumulated in materials and products. Long-lasting applications, a late increase of cadmium use in batteries not yet discarded, and possibly irregularities in e.g. waste disposal data may together account for this enormous accumulation figure. Eventually, this quantity will end up in the environment, and may be regarded as a true 'cadmium time bomb'.

[2] A very important source has been the report of the ERL (1989) on cadmium sources, drafted for the Commission of the EC. A further specification of the various stocks and flows and the underlying data can be found in Van Egmond (1990) and Huppes et al. (1992).

Figure 7.1 Substance Flow Diagram for cadmium within the European Community, 1987 (in tonnes Cd).



The diagram is divided into an economic and an environmental subsystem. Both subsystems have an inflow side: import, formation and recovery (top, 1-6) and an outflow side: export, degradation and immobilization (bottom, 7-12). In addition, there is an interchange between the two subsystems: emission into, and extraction from the environment (13 and 14). Accumulation can occur in both subsystems (15 and 16). In the economy this means the stockpiling of raw materials and products. In the environmental subsystem a distinction is made between the various environmental segments in which accumulation can occur. Finally, both systems also include processes. These in fact determine the course and distribution of the substance flows, and their potential transformation. In the economic subsystem these are processes tied up with production, use and waste treatment; in the environment it concerns evaporation, deposition, leaching, sedimentation and suchlike. The diagram as pictured in Figure 7.1 in fact represents the result of all processes combined, and should be regarded as the summary of the Substance Flow Analysis.

Environment

As can be seen, 'natural' cadmium sources (transboundary inflow and volcanic activity) are minor compared to the economic sources. Almost all Cd emitted to the environment will end up as environmental accumulation (3063 tonnes/year in 1987). The bulk, roughly 2400 tonnes/year, consists of landfill; temporary storage on industrial premises is included as well. Accumulation in soils is also extensive. For agricultural soils, the chief source is use of phosphate fertilizers. The net accumulation of 406 tonnes Cd/year (see Figure 7.2) means an average annual accumulation of 3 g/ha, or 4.5 μg/kg soil[3]. In some areas, accumulation will be lower, but in others significantly higher, leaving only a short time span for either the soil concentration or the cadmium content of food products to transgress environmental and health standards. For natural soils, the main source is atmospheric deposition. In these soils, too, there is a concentration build-up, although at a slower pace (ca. 0.5 g/ha.year). The annual increase in concentration in sediments is significantly larger: a net accumulation of 66 tonnes/year means 16 g/ha or 25 μg/kg. In sedimentation areas, especially, this represents a major threat to ecosystems.

Differences within the European Community

Concerning Cd emissions to the various environmental segments, there appear to be important differences between (groups of) EC member states.

With regard, first, to mean atmospheric emissions per km², Belgium and Luxemburg, the Netherlands, (former) Western Germany and the UK have the highest atmospheric emissions and Greece, Portugal, Spain, Ireland and Denmark the lowest. France and Italy hold an intermediate Position. These differences are probably due to the fact that in the first group of countries there are more polluting industries, e.g. zinc refineries, and considerably greater waste incineration capacity than in the other countries.

Comparing diffuse emissions to the soil (use of manure and P-fertilizers), a similar pattern can be observed: the greatest pollution per square kilometre of agricultural soil occurs in Belgium, the Netherlands, Germany and Ireland, with very low emissions in Portugal, Spain, Greece and Denmark. The same appears to be true for landfilling of Cd-containing waste, but this time France, Spain and Italy are also among the more polluted countries.

In general it can be stated that, with respect to environmental emissions, there is a division within the EC which appears to be associated with the level of economic development. In this respect, Denmark forms an exception. Here, a relatively high level of economic development is accompanied by a low level of pollution. It would be an interesting line of investigation to make comparisons in greater detail, in order to identify the underlying causes and formulate expected future trends with regard to the exceptional position of Denmark.

7.3.3 The economic origins of cadmium-related environmental problems

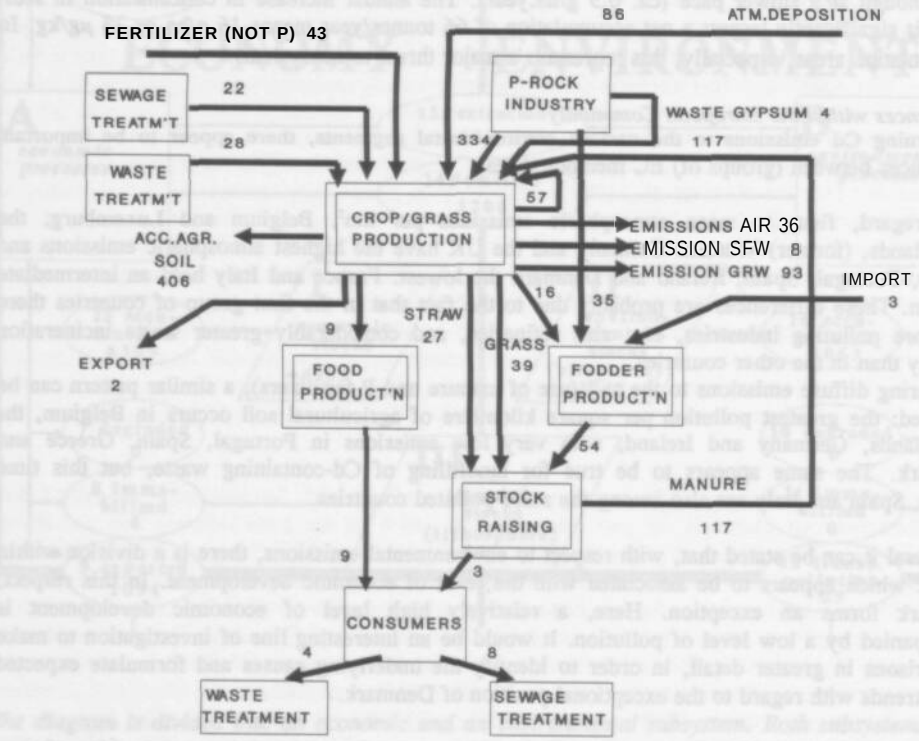
To trace the economic origins of environmental cadmium problems, a further specification of economic Cd routes is required, and of the way these are connected. In the present analysis, we have opted for a level of specification in which each branch of industry handling Cd forms a single unit connected to other units by Cd flows. As there are a great many industries involved, and other sectors besides, the whole overview is too complex to fit into a two-dimensional diagram. As an example, Figure 7.2 gives a more detailed view of a small but not unimportant Part of the 'economic processes' box of the SFD: the food production and consumption sectors. For other sectors, comparable diagrams have been drawn up. For each unit, the inflows and out-

[3] Assumption: Cd accumulates in the top 10 cm of the soil, and the average soil weight is 1.5 kg/l.

flows must balance. The overall materials balance of Figure 7.1 is thus made up of many small materials balances interconnected in many ways.

Still finer specifications are possible and may be desirable depending on the goal of the analysis. For an overview of flows and stocks for as large an area as the EC, we did not consider this necessary, because relatively small changes do not influence the rather robust type of statements that can be made at this level.

Figure 7.2 Economic cadmium flows related to food production and consumption within the EC, 1987 (in tonnes Cd).



Pollution problems

The following individual pollution problems have been identified above: health hazards through food consumption, ecotoxicological risks to aquatic ecosystems, and local problems from Cd waste disposal. As a fourth, the economic accumulation of Cd is selected: if only because of its magnitude it constitutes a major risk for a future rise in emissions. As long as the Cd is still used, there is no environmental harm. Every product however will one day be disposed of. It can be argued that ways of waste disposal are being developed that slow down emissions into the environment to an almost 'geological' level (in the SFD, this is classified under 'immobilization'[4]). Whether these techniques will be adopted on a significant scale, is unclear at this moment.

[4] In the present situation, only the disposal of harbour sludge in the Dutch Slufter is considered to be 'immobilized'.

Table 7.1 Economie origins of cadmium-related environmental problems, 1987

	10^3 kg	% of total load
Agricultural soil load		
* direct load		
fertilizer	377	59%
manure	117	18%
other org. fert.	54	9%
atmospheric deposition	86	14%
TOTAL	*634*	700%
* economic sectors responsible		
agriculture	511	81%
consumers	62	10%
industries	34	5%
energy production	17	3%
other	0	0%
non-economic	10	2%
TOTAL	*634*	*100%*
* ultimate origins		
phosphate rock import	505	80«
zinc ore import/recovery	71	11%
cadmium import	15	2%
other ore import/recovery	5	1%
fodder import	4	1%
fossil fuel import/recovery	22	3%
transboundary inflow	0	0%
natural origins	12	2%
TOTAL	*634*	*100%*
Surface water load		
* direct load		
industrial discharges	58	36%
sewage water discharges	54	33%
atmospheric deposition	2	1%
losses from sites	24	15%
losses from soils	6	4%
transboundary inflow	17	10%
TOTAL	*161*	*100%*
* economic sectors responsible		
agriculture	6	4%
consumers	14	9%
industries	123	76%
energy production	0	0%
other	1	1%
non-economic	17	10%
TOTAL	*161*	*100%*
* ultimate origins		
phosphate rock import	61	38%
zinc ore import/recovery	64	40%
cadmium import	16	10%
other ore import/recovery	3	2%
fossil fuel import/recovery	0	0%
transboundary inflow	17	10%
natural origins	0	0%
TOTAL	*161*	*100%*

Table 7.1 (continued)

	10^3 kg	% of total load
Landfill (incl. temporary waste storage)		
* **direct load**		
industrial waste		
- jarosite	576	24%
- other	821	34%
household waste		
- direct landfill	698	29%
- incineration residues	67	3%
waste from energy production	31	1%
car wrecks & demolition waste	169	7%
sewage sludge	27	1%
dredged materials	39	2%
TOTAL	*2428*	100%
* economic sectors responsible		
agriculture	2	0%
consumers	**885**	36%
industries	1426	59%
energy production	31	1%
other	80	3%
non-economic	4	0%
TOTAL	***2428***	100%
* ultimate origins		
phosphate rock import	221	9«
zinc ore import/recovery	1536	**63%**
cadmium import	334	14%
other ore import/recovery	**292**	12%
fossil fuel import/recovery	41	2%
transboundary inflow	4	0%
natural origins	0	0%
TOTAL	***2428***	100%
Economic accumulation		
* direct load		
zinc products	**497**	7%
cadmium products	**6585**	89%
iron and steel products	**32**	0%
products from crude oil	**25**	0%
building materials	176	2%
road constr. materials	66	1%
TOTAL	***7381***	100%
* economic sectors responsible		
end use of materials/products by industries, consumers and in buildings or roads	**7381**	100%
TOTAL	***7381***	100%
* ultimate origins		
phosphate rock import	13	0%
zinc ore import/recovery	4677	**63%**
cadmium import	2523	34%
other ore import/recovery	138	2%
fossil fuel import/recovery	30	0%
transboundary inflow	0	0%
natural origins	0	0%
TOTAL	***7381***	100%

These problem flows can be traced back to their economic origins. To this end, they are first translated into the terms of the SFD:

1. The consumption of Cd in food products can be traced back to Cd accumulation in agricultural soils, and therefore to the agricultural soil load.
2. The high concentrations in aquatic systems can be related to the surface water load.
3. Local problems can be related to the disposal of Cd-containing waste on landfill sites or on industrial premises.
4. **The economic accumulation of Cd is due to stockpiling or use of durable (> 1 year) Cd applications in various products and materials.**

The economic origins are divided into three categories, from the environmental segment concerned back into the economic chain: the direct load, the economic sectors responsible for this load, and the ultimate origins: import and production. Table 7.1 specifies the economic origins of the four problems mentioned.

For accumulation in agricultural soils, the unintentional use of Cd in (industrial and animal) fertilizer products is the most important source, making agriculture itself the sector responsible. Ultimately, this can be traced back almost entirely to the import of phosphate rock, which contains Cd as an ore contaminant. Another major contribution is due to atmospheric deposition, caused by emissions from various ore-refining industries and combustion of fossil fuels (through unintentional occurrence of cadmium), and to a lesser degree from cadmium application industries and municipal waste incineration (intentional cadmium use).

The surface water load is due mainly to discharges by industry, of which the most important is the phosphate industry. Ultimately, the main sources are import of phosphate rock and import and extraction of zinc ore. Again, the unintentional occurrence of cadmium is more important than the intentional applications.

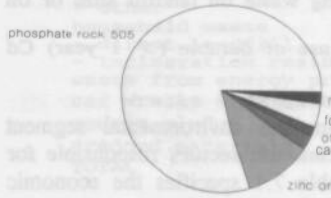
The landfill discharge is due largely to industrial waste storage. A large amount of Cd occurs in jarosite, a waste product from the zinc industry. Other sources are the iron and steel industry (iron ore and recycling of scrap, ultimately again from zinc ore), the cement industry (iron refinery waste and limestone) and various Cd-application processes (zinc ore again). There is also a substantial influx from the disposal of municipal waste. A major proportion of the Cd can be traced back to (intentional) use in various products such as pigments and stabilizers. Ultimately, this Cd comes from the import or recovery of zinc ore.

Economic accumulation, which is bound to enter the waste stage and therefore end up in the environment at some time in the future, is due almost entirely to the accumulation of Cd-containing products in the more durable applications. Ultimately, zinc ore and Cd import (that is, zinc ore abroad) can be traced as the major origin of economic accumulation. It is intentional Cd use that is responsible for the magnitude of this accumulation. The increase of Cd use in batteries since the reference year, 1987, is substantial. Economic accumulation will have increased accordingly, while the appearance of the batteries in municipal waste is expected to become apparent around now.

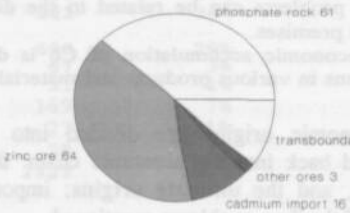
The various problematical flows appear to have two major ultimate origins: phosphate rock and zinc ore. The more diffuse emissions are due mainly to products and processes of the phosphate industry, where Cd occurrence is unintentional. For the more 'manageable' landfill and economic accumulation, the intentional applications of Cd and therefore zinc ore constitute the main origin. This is represented in Figure 7.3.

Figure 7.3 Ultimate origins of the various problematical flows compared (in tonnes Cd, 1987).

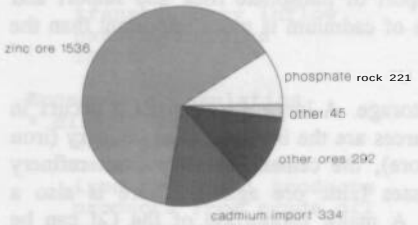
7.3a agricultural soil load



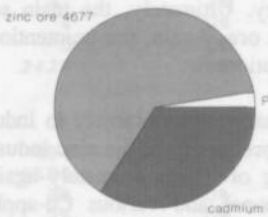
7.3b surface water load



7.3c landfill



7.3d economic accumulation



7.3.4 **Trends in cadmium pollution problems**

Trends in recent years

The import of batteries has increased considerably, approximately quintupling over the period from 1987 to 1990. This implies an even larger rise in the demand for these batteries than was expected (Eurostat Foreign Trade, 1990). If no additional measures are taken, this will result in a proportionally large increase in the Cd content of household waste, consequently leading to higher landfill emissions (disposal of municipal waste) and air emissions (waste incineration).

With regard to the use of phosphate fertilizers, recent trends are as follows: in countries with high fertilizer consumption levels use has now started to decrease, while in more 'modest' countries use is now increasing (FAO, 1987/1990). The total amount of P-fertilizer used in the EC has remained approximately stable the last few years.

There has been a slight decline in Cd pollution of surface waters: in some rivers such as Elbe and Rhine the Cd load has diminished, but in others (Meuse) it has increased.

Future developments

Based on recent trends, predictions can be made about the possible gravity of the Cd problem in the years ahead. Several applications of Cd will possibly diminish or even disappear as a result of environmental policies. Others, and especially NiCad batteries, are expected to increase significantly. Overall, the intentional use of cadmium will most probably still increase. In time, therefore, so will the emissions from industries and the generation of waste to be treated in one category or another. It is to be expected that the trend of decreasing industrial emissions to the atmosphere and surface water at a stable or even increasing production level (Stigliani et al., 1992) will continue. In that case, a shifting to a larger solid waste generation can be expected.

With regard to the use of P-fertilizers, a further decrease is expected in several countries (for instance the Netherlands and Germany) as a result of more stringent regulations concerning nutrient management. The accumulation of Cd in agricultural soils will therefore continue at a somewhat slower pace in the current problem areas. In the other countries, however, fertilizer use will most probably increase. This will eventually result in a higher average Cd concentration in the agricultural soils of the EC as a whole and, with time, new problem areas will emerge.

In general, it is to be anticipated that Cd pollution problems will increase. As a result of the long-term retention of Cd in soils, sediments, sludges and groundwater, only measures verging on a complete phase-out of emissions will prevent Cd concentrations from rising. And even then, there will be an extensive amount of Cd accumulated in the economic system to get rid of, causing waste generation for many years after the phase-out. However, the expectations are that emissions will even increase, and therefore also the speed of accumulation.

So far, we have only treated problems related to Cd pollution. Quite another problem, however, is the depletion of supplies. In the long term, as the supply of zinc ore runs low, the amount of Cd available will be determined largely by the extent of recycling and previously stored Cd. As long as primary zinc continues to be produced, the pollution problem will dominate. Since it is unknown to what extent secondary zinc will be used and Cd kept circulating in the economy (for example by recycling), no attempt has been made to forecast the gravity of these problems.

7.4 Ways to solve the cadmium problem

7.4.1 General strategies

A sustainable solution to the cadmium problem should take into account both the pollution and the depletion problem. The most effective source-oriented abatement measure is obviously to reduce production and use of the substance, focusing especially on dissipative uses[5]. Additionally, the strategy of 'closing economic cycles' is suitable for controlling both problems: minimizing losses from the economic system and (therefore) recycling of waste[6]. Both options, generally speaking, prevent pollution on the one hand, and delay depletion on the other. An increase in the efficiency of economic processes, in the production phase as well as during use and waste disposal, is therefore required. However, in the case of cadmium the results of the analysis in Section 7.3 appear to question the absolute validity of these generally accepted strategies.

In its intentional uses, Cd is a by-product of zinc. Therefore, measures aimed at achieving a decrease in Cd applications do not influence its initial recovery. This is even truer for phosphate, in which Cd occurs as a contaminant. To tackle the Cd problem on the inflow side, measures must therefore focus not only on Cd but simultaneously on zinc and phosphate.

In the case of Cd, closing economic cycles through recycling appears to generate new problems as well. In general, recycling directly influences the economic inflow: the need for freshly mined stocks will be less. As the recovery of cadmium is entirely non-intentional, however, this direct link between recycling and inflow does not exist. Recycling, on the contrary, will further increase Cd availability: Cd that would otherwise enter the waste stage will be added to the economic stock again. Increased availability will lead to a growth in Cd applications. As the most concentrated Cd applications will necessarily be recycled, there will be a net shift from concentrated to more diffuse cadmium applications, leading to larger (and less manageable) emissions in the future. For an effective cadmium policy, it seems that other strategies and rules are required.

In the next section, the actual (physical) measures of the EC's proposed policy on cadmium are specified, and the effectiveness of this package of measures is estimated. The EC's policy has been drafted along the general lines of influencing production and use of Cd, minimizing economic losses and stimulating recycling. It therefore offers a test case for the above speculations. In considering the results presented in the next section, though, it should be borne in mind that no consideration has been given to costs or any implementation and control problems. It therefore represents an unrealistically optimistic estimate of the changes that can be expected in Cd flows. In reality, the impact of the policy package can be expected to be considerably less pronounced, but in the same direction, however.

7.4.2 EC cadmium policy

Roughly speaking, the EC's proposed cadmium policy (Commission of the European Communities, 1988; partly realized in directives (Council of the EC, 1990 and 1991)) comprises

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[5] *The importance of dissipative uses of chemicals, including Cd, for emissions into the environment has been stressed by Ayres et al. (1989).*

[6] *While a full ban on cadmium is disputed, policy makers and industrial organizations agree about collection and recycling (Hewitt & Hiscock, 1988).*

the following elements:

1. Technical, end-of-the-pipe emission reduction for large point sources of emissions to air and surface water.
2. Prohibition of most Cd applications as a pigment or stabilizer.
3. Collection and recycling of Cd-containing batteries, in which Cd occurs in relatively high concentrations.
4. **Setting a standard for Cd concentrations in fertilizers.**

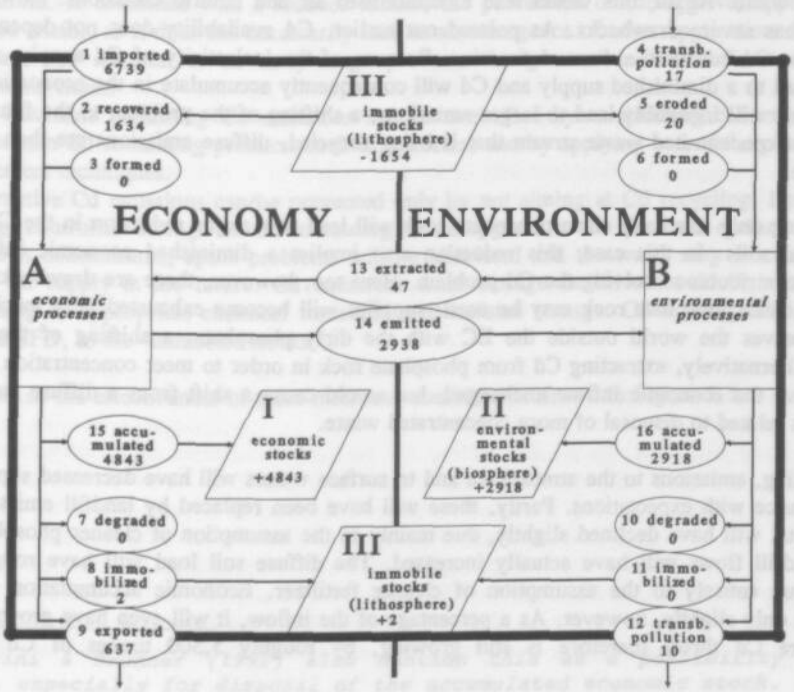
This policy is therefore in line with the standard strategies of decreasing production and use on the one hand, and closing economic cycles on the other. In Figure 7.4, the effectiveness of the above measures combined is calculated and translated into changes in Cd flows. A very simplistic and optimistic 100%-effectiveness assumption has been made concerning implementation of the various measures:

- All industrial emissions into air and surface waters are assumed to be reduced by 90%.
- Pigment and stabilizer applications, amounting at present to more than 3000 tonnes Cd/year, are assumed to have disappeared completely.
- Recycling of batteries is assumed to be 50% efficient.
- Clean fertilizer products are assumed to be available through use of cleaner phosphate rock rather than through extraction of Cd from the rock, which would only create an alternative waste stream. Total substitution by a Cd-poor grade of ore is assumed to be both physically and economically possible.

The figures in Figure 7.4 therefore represent the theoretical maximum effectiveness of a policy in this direction and bear no relation to any realistic expectations.

The expected impact of the individual policy measures outlined above is discussed below.

Figure 7.4 Estimated cadmium flows in the EC as a result of the EC's cadmium policy (in tonnes Cd/year)



Ad 1. In industries and municipal waste incineration plants, 90% of Cd emissions could theoretically be prevented by installing flue-gas filter systems. In that case, the fly ash and sludge resulting from this treatment will contain more Cd, and diffuse emissions to the atmosphere will be replaced by landfill emissions following disposal. Use of fly ash, in building materials for example, will prevent emissions in the short term. Eventually, however, this Cd will end up as building and demolition waste, again entering the environment though at a slower pace. Whether the disposal of this waste can be characterized as 'immobilization' is not clear; the assumption here is that it cannot.

Ad 2. The prohibition of Cd applications in low concentrations will immediately lead to a very significant lowering of the Cd content in household waste, and so reduce emissions into air and landfill. However, this measure has certain consequences that act in the opposite direction: the economic availability of Cd will actually increase, because the inflow does not decrease accordingly. Only the (net) import of raw Cd is assumed to respond to this change and is, again optimistically, supposed to disappear completely. Import and co-recovery with zinc ore remains at the same level, because zinc flows are not influenced. A further reduction of Cd application will no longer reduce the inflow at all. Therefore, Cd will find its way into other, non-prohibited applications. This, too, will eventually lead to an increase in Cd emissions when the (presumably more concentrated and longer-lasting) Cd-containing products in question reach the waste stage. The unintentional occurrence of Cd in zinc products (approximately 10% of total intentional use) will not be greatly affected. Only in the case of very effective overall Cd abatement measures (including strict standards for the Cd content of zinc products) will economic use decrease. Cadmium then becomes a waste product of the zinc industry. Most probably, it will be dumped on landfill sites or even worse. Again, this means shifting the problem from diffuse emissions to landfill.

Ad 3. Collection of Cd-containing products, especially batteries, prevents their ending up in household waste. Again, this would lead to diminished air and landfill emissions. However, Cd recycling has severe drawbacks. As pointed out earlier, Cd availability does not depend on the demand for Cd but on the demand for zinc. Because of the inelasticity of Cd supply, recycling will not lead to a diminished supply and Cd will consequently accumulate in the economic system. In time, this will inevitably lead to larger emissions: a shifting of the problem to the future. As it is the most concentrated waste stream that is being recycled, diffuse emissions are then expected to increase.

Ad 4. Using only relatively clean phosphate rock will lead to a major reduction in the Cd load of agricultural soils. In this case, this reduction also implies a diminished economic inflow, and therefore contributes to solving the Cd problem. Here too, however, there are drawbacks: if only relatively clean phosphate rock may be used, supplies will become exhausted very much sooner. Also, it leaves the world outside the EC with the dirty phosphate: a shifting of the problem abroad. Alternatively, extracting Cd from phosphate rock in order to meet concentration standards would leave the economic inflow unchanged, but would cause a shift from a diffuse emission to discharges related to disposal of more concentrated waste.

Summarizing, emissions to the atmosphere and to surface waters will have decreased significantly, in accordance with expectations. Partly, these will have been replaced by landfill emissions. The landfill total will have declined slightly, due mainly to the assumption of cleaner phosphate rock. Other landfill flows will have actually increased. The diffuse soil load will have roughly been halved, due entirely to the assumption of cleaner fertilizer. Economic accumulation will have decreased only slightly, however. As a percentage of the inflow, it will even have grown slightly. The future Cd threat therefore is still growing, by roughly 5,500 tonnes of Cd per year

stockbuilding. Batteries, both still in use and recycled, are responsible for a major share of this accumulation.

It is clear that all the proposed measures constitute no more than a short-term solution. Within a longer-term perspective, they all lead to increased emissions either within or outside the EC. The EC policy, on the surface, conforms to the notions of sustainable development. In reality, though, it does not solve the cadmium problem. The least source-oriented measures, end-of-the-pipe emission reduction and the removal of cadmium from phosphate fertilizer, are perhaps the best options, as they shift the problem from diffuse to local emissions (a step in the direction of 'immobilization') without any hidden hazards. The most important reason for the ineffectiveness of a policy of this type in the long run is that the fact that cadmium is entirely recovered as a by-product of zinc is not taken into due account. Minimizing losses, either by means of a product-oriented policy or by recycling without additional measures, does not appear to be a feasible route for sustainable cadmium management.

7.4.3 Managing cadmium in a sustainable way

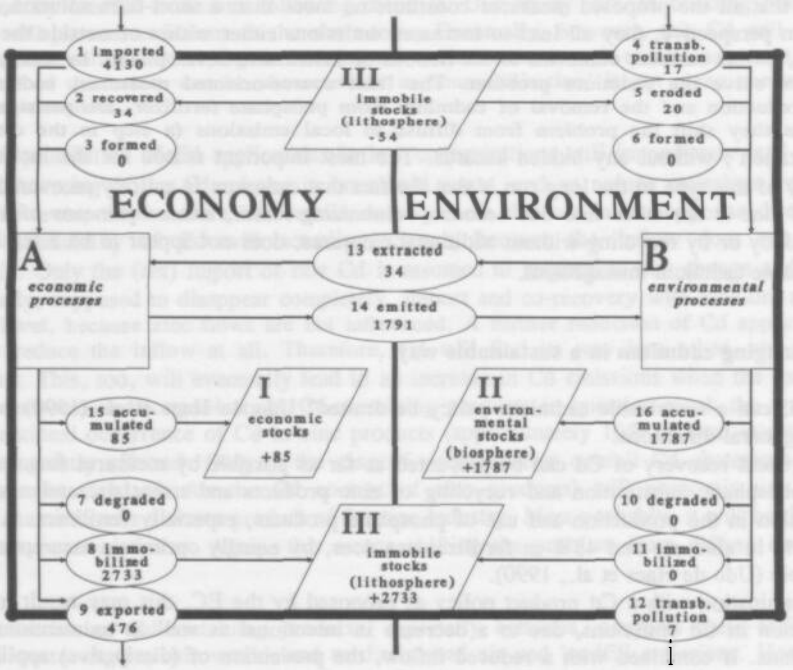
How, then, can a sustainable cadmium policy be drafted? Udo de Haes et al. (1990) outline the following general directions:

a. Import and recovery of Cd can be prevented as far as possible by measures focused on zinc and phosphate: substitution and recycling of zinc products and materials, and a significant reduction in the production and use of phosphate products, especially fertilizers. A decrease of 60% in zinc use and 45% in fertilizer use does, by equally optimistic assumptions, seem possible (Udo de Haes et al., 1990).
b. In combination with a Cd product policy as proposed by the EC, this may result in a major reduction in Cd emissions, due to a decrease in intentional as well as unintentional Cd applications. If combined with a reduced inflow, the prevention of (dissipative) applications is indeed useful, as it does not necessarily lead to an emergence of other applications. Declaring Cd a waste material at an early stage prevents the generation of emissions during the economic chain.
c. The inevitable remaining Cd emissions can be controlled by establishing collection systems for certain Cd-containing products such as batteries, and by applying end-of-the-pipe emission abatement techniques.
d. Alternative Cd emissions can be prevented only by *not* aiming at Cd recycling. For the time being, controlled storage of Cd-containing waste appears to be the best option. If the Cd waste is concentrated, space problems will be alleviated and the waste may eventually serve as a Cd supply in the future. Cd emissions from storage facilities should be prevented by choosing an appropriate chemical form and well-isolated storage. Cd is thus added, in terms of the SFD, to the 'immobile stocks'[7].

An estimate of the effectiveness of these measures combined is shown in Figure 7.5.

[7] Baccini & Brunner (1991) also mention this as a possibility for Cd control, especially for disposal of the accumulated economic stock.

Figure 7.5 Cadmium flows in the EC as a result of the alternative cadmium abatement measure package (in tonnes Cd/year).



The emission reduction achieved in the short term does not represent a great improvement over that resulting from an effective EC policy along the proposed lines. In the long term, however, the improvement is very substantial from both a pollution and a depletion point of view, because the emission reduction in this scenario is in fact linked to a reduced economic inflow. The collected Cd-containing products do not accumulate in the economic system, but are 'stored for the future' and therefore added to the immobile stocks. Economic accumulation is therefore very much lower than is to be expected from a successful EC policy. However, there is still accumulation. In future, an even stricter package of abatement measures seems to be required, principally based on an even larger reduction of the zinc and phosphate inflows.

7.5 Generalization to other substances

In their general principles, the results obtained for the case of cadmium are directly translatable to other metals recovered only or mainly as ore contaminants. For these metals, recovery and economic availability is virtually unrelated to demand. Changes in demand resulting, for example, from a prohibition of certain applications thus do not influence the inflow but only the price, leading to a growth of other applications. Increased availability as a result of recycling does not automatically lead to diminished recovery but only to a lower price, assuming a steady demand. Recycling is a possibility, however, for the intentionally recovered main ores. Environmental problems related to the recovery of ore contaminants can, on the inflow side, only be tackled

through the main products.

With such ore contaminants, occurrence in economic products can be both intentional and unintentional (as a product contaminant). The scale of unintentional use depends directly on the use of the main material, or to remove the contaminant from it. Because the substances concerned are elements, destruction is impossible. Once they have found their way into the economic system, the only way to avoid emissions is either to keep them circulating within the economic system forever, or to dispose of them through the 'immobilization' route, preferably in such a way that they may be added, if required, to the world's stock.

A still more general picture emerges from the above, applying the same principles to all substances: the effectiveness of any given measure, however source-oriented and cycle-closing it may be, depends on the way the substance enters and finds its way through the economic system. Recycling and substitution are useful in the case of substances intentionally recovered or produced. For some substances, substitution by other materials will contribute to the solution. In the case of others (carbon, oxygen, nitrogen, phosphorus), substitution is in many cases unfeasible because they fulfil elementary functions for human (and other) life. Designing a really effective and sustainable substance policy is only possible on the basis of what may be called the *economic characteristics* of the substance in question. These characteristics are the economic pendant of the environmental characteristics of a substance, on which its management policy is founded. They are related to supply and demand, and therefore determine the economic pathways of materials. Both are rooted in the physical properties of the element or compound in question.

The environmental characteristics of substances are of overriding importance for the formulation of policy *goals* in terms of concentration limits and emission reduction levels. Important Parameters include:
- type and extent of environmental impacts;
- degradability and persistence;
- accumulation characteristics.

Actual abatement measures, however, must be determined by the economic characteristics of the substances. From the analysis of cadmium flows, two such characteristics have been identified:
- intentionality of recovery or production;
- intentionality of use.

Other characteristics can probably be identified, and there appears to be a wide field of research and speculation still open in this direction.

7.6 Conclusions

1. The economic production and use of cadmium in the EC leads to severe environmental Problems. Based on a substance flow analysis, the following problem flows have been identified, m increasing order of manageability:
- agricultural soil load;
- surface water load;
- landfill sites;
- economic accumulation.

A variety of direct causes can be identified for these problem flows, and ultimate responsibility traced back to a limited number of economic sectors. These sectors are the same for each problem flow, but with varying contributions in each case. Ultimately, the Cd flows can be traced back to two main economic inflows: the import of phosphate rock and the import or extraction of zinc

ore. Zinc ore is the main source of the intentional applications of Cd, which end up mostly on landfill sites or accumulating in the economy. In phosphate rock Cd occurs as a contaminant, polluting the most important P-product: fertilizer, and causing Cd to circulate in the economic-environmental agricultural system.

2. For a successful cadmium policy, the generally accepted notions of source-oriented policy and recycling appear to have to be amended in this special case. The EC policy, according to the proposed lines of (1) end-of-the-pipe measures, (2) a phase-out of certain applications, and (3) recycling of batteries and plating, conforms to those notions. Various forms of problem shifting are expected to appear:

- diffuse emissions will be replaced by local emissions;
- emissions within the EC will be replaced by emissions outside the EC;

and most importantly:

- emissions now will be replaced by emissions at a later date.

This policy does not appear to offer a sustainable solution to the cadmium problem, mainly because it does not consider the inelastic nature of cadmium supply: mostly as a by-product of zinc.

3. In order to be effective, a cadmium policy must take into account the way Cd enters and filters through the economic system. On the inflow side, measures must be directed not at Cd but at the main products, zinc and phosphate. Otherwise, Cd-oriented measures such as battery recycling only lead to increased Cd availability and thus to larger future losses to the environment. On the outflow side, collection of Cd-containing waste and products and subsequent safe storage in a concentrated form seem to offer the best solution both from a pollution and from a depletion point of view.

4. To a certain extent, these conclusions can be generalized to other substances. All ore contaminants, recovered wholly or mainly as a by-product of other materials, will exhibit more or less the same behaviour. Substances occurring as a contaminant in products will require a different policy from intentionally applied materials. Still more generally, characteristics related to economic supply and demand such as intentionality of recovery and intentionality of use may be an indispensable basis for a successful substance-oriented policy.

7.7 Acknowledgements

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CHAPTER 8 NITROGEN POLLUTION IN THE EUROPEAN UNION[1]

8.1 Origins and proposed solutions

8.1.1 Introduction

Eutrophication, literally the enrichment of the environment with nutrients, is a problem occurring on a large scale in the developed world and especially in the European Union (EU) (Commission of the EC, 1992b). In fact, not one but several problems arise from the excessive addition of nutrients to the environment: eutrophication of rivers and lakes, acidification and eutrophication of terrestrial natural areas, nitrate contamination of groundwater, phosphate saturation of agricultural soils, and eutrophication of coastal seas. These problems occur on different scale levels, the actual effects are different, and even in their immediate origins they vary. For all of them, however, an important cause is an imbalance of the nutrient budgets of the systems involved (UNEP, 1992; Brandenburg et al., 1992).

So far, environmental policy moves to tackle nutrient-related problems have been undertaken on different scale levels: subnational, national and supranational. The eutrophication of coastal seas is on the international problem list. The United Nations have stated the eutrophication of seas to be a subject for immediate global concern and have urged the national governments to regulate this 'marine pollution from land-based sources' (UNCLOS art. 207) in their environmental policies. The countries involved have concluded international agreements in the Paris Convention for the North Sea (1974) and the Barcelona Convention for the Mediterranean (1976). Atmospheric deposition of acidifying compounds is also an internationally acknowledged problem. Agreements have been made by European countries to reduce the emissions in question. The other problems are treated by EU countries in widely differing ways (Noorduyn & Van Dijk, 1991). Some countries have manure policies on a national level, in others the issue is regulated by federal states, provinces or counties, while yet others do not regulate at all. The question, then, is whether the coherence between the individual problems, whether in origins or in effects, justifies a supranational approach for the pack of them or not. Springer (1983) gives three criteria for taking a supranational approach to environmental problems:

1. in the case of transboundary pollution;
2. in the case of damage to the 'res communis', or common property;
3. in the case of local problems for which the solution has international implications, which may be another way of saying: in the case of local problems with international (economic) origins.

In this article, the focus is on one of the most important nutrients: nitrogen in its various compounds. It is argued that all three criteria for a supranational approach are met in the case of nitrogen. The European Union has been chosen as the region studied, for two different reasons: (1) nitrogen-related environmental problems are apparent in many parts of the EU, and (2) the European Community (EC) is a supranational institution with regulatory powers. The purpose of this article is twofold:

- to identify the (economic) origins of various nitrogen-related environmental problems, and to

[1] This chapter contains two articles, both submitted to *Environmental Conservation.* One of the two, here Chapter 8.1, is accepted for publication in revised form: Voet, E. van der, R. Kleijn & H.A. Udo de Haes. Nitrogen Pollution in the European Union - Origins and Proposed Solutions. *Environmental Conservation,* in press. The other one, Chapter 8.2 of this thesis, is still being reviewed: Voet, E. van der, R. Kleijn & H.A. Udo de Haes. Nitrogen Pollution in the European Union - an Economy-Environment Confrontation Submitted to *Environmental Conservation,* 1994.

establish any connections between these problems;
- to investigate the effectiveness of internationally agreed or intended options for solving the aforementioned problems.

In section 8.1.2, the method of investigation is discussed. After that, the individual nitrogen-related problems within the EU and their interconnections are investigated by analysing the flows of nitrogen (N) through the EU in section 8.1.3. The origins of three different nitrogen-related problems are traced in section 8.1.4. In section 8.1.5, existing policies on an international level of relevance to nutrient-related problems are discussed. These policies include the Common Agricultural Policy (CAP) and the recent changes according to the so-called McSharry Plan. The impacts of a package of measures consisting of probable trends and policy measures impacting on N flows are calculated in section 8.1.6. In section 8.1.7 finally, the results of these calculations are discussed.

8.1.2 Methods and materials

General description of the SFA method

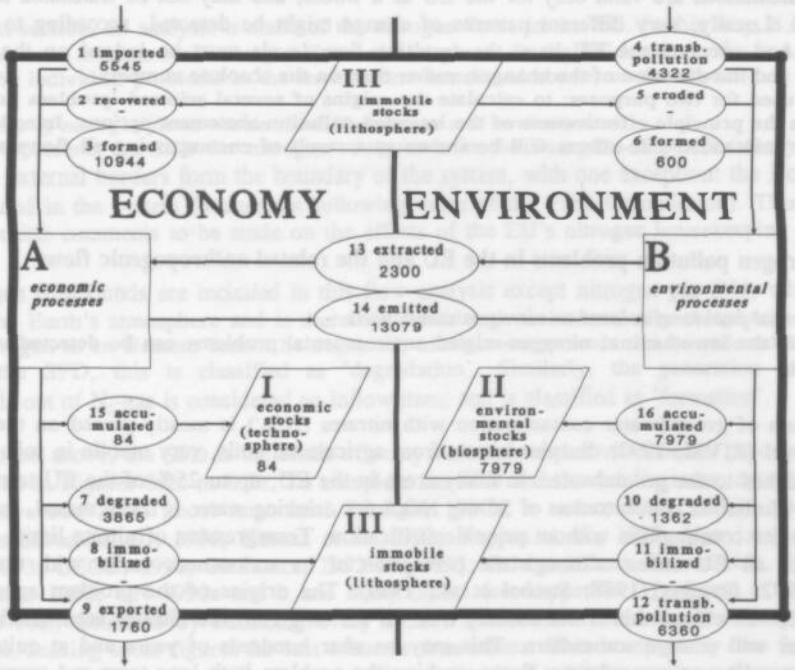
For the analysis of nitrogen flows within the EU area, the Substance Flow Analysis (SFA) method as described by Udo de Haes et al. (1988) and used in various studies (Huppes et al., 1992; Van der Voet et al., 1993; Kleijn et al., in press) has been adopted. This method starts from the materials balance principle (described and used for the analysis of nitrogen flows i.a. by Ayres et al. (1989), and in a regional nitrogen balance study by Brunner & Baccini (1992), Doluschitz et al. (1992), and Fleckseder (1992)). The crux of the SFA method is the integrated examination of *all* flows of a substance or a group of substances within a defined geographic system, encompassing both its economy and its environment. The framework of the SFA method can be visualized as the Substance Flow Diagram (SFD), shown in Figure 8.1. The diagram is divided into a subsystem for the economy and one for the environment. In the system, a distinction is made between flows of substances (ovals in Fig. 1), stocks of substances (diamonds), and processes involved in changing and subdividing substance flows (squares). The figures in Figure 8.1 represent ktonnes of nitrogen in the EU in 1988. A further specification is given below, in the section treating the nitrogen flows in the EU.

Flows
Both subsystems have an inflow side: import from other systems; recovery or erosion from system stocks; and formation 'out of nothing' (i.e. from basic elements or from other compounds) (top, 1-6). Both subsystems also have an outflow side: export to other systems, degradation, and (re)addition to stocks (bottom, 7-12). In addition, there is an interchange between the two subsystems in the form of emissions to, and extraction from the environment (centre, 13 and 14).

Stocks
Accumulation (or depletion) can occur in both subsystems (15 and 16). In the societal subsystem, this not only means the stockpiling of raw materials or products, but also includes the temporary storage of waste materials on industrial premises. In the environmental subsystem, a distinction can be made among the various environmental compartments in which accumulation can occur: soil (locally or diffusively), sediment, groundwater or biota. In the system's 'immobile stocks', accumulation or (as will more often be the case) depletion are also made visible.

Processes
The processes form the central item in each subsystem. These in fact determine the course and

Figure 8.1 Substance Flow Diagram (SFD) for nitrogen compounds in the European Union. In ktonnes N, 1988.



distribution of the substance flows, and their possible transformations. In terms of the economy, these are processes tied up with production, consumption and waste treatment; in the environmentthe processes involved are physico-chemical processes (evaporation, deposition, leaching, sedimentation, decomposition etc.) and biological processes (bioaccumulation, biodégradation etc.). Figure 8.1 in fact represents the result of all processes combined, and should be regarded as the most general summary of the SFA analysis. In order to determine the pathways of a substance or group of substances in a quantitative manner, these underlying economic and environmental processes must be investigated.

Application of the SFA method: SFINX

In order to obtain an overview of the actual situation in the EU, it suffices to make an inventory of flows, provided the data are available. However, to trace the origins of specific pollution problems or calculate the impacts of certain abatement measures requires a certain degree of modelling: the relations between the various flows and/or stocks must be specified. For a real scenario analysis, which is not attempted in this article, the required modelling would be quite extensive and would have to encompass both flows and stocks.

For the purposes of this article, calculations have been made with the computer program SFINX (Substance Flow InterNodal eXchange) (Van Oers et al., 1994). The relations between the flows are modelled as linear equations, and no stocks are specified. With SFINX, the long-term equilibrium situation resulting from a given nitrogen management regime is calculated; no dynamic aspects, meaning the time span required to reach this equilibrium and the path towards it,

are involved. In view of the swiftness of the economic N-cycle, expectations are that this time span will not be long (less than 10 years). Moreover, no spatial differentiation is made: the results of these calculations are valid only for the EU as a whole, and may not be translated to a lower scale level. Locally, very different patterns of change might be detected, according to the local situation. And even on the EU level the resulting flow levels must be judged on the order of magnitude and the direction of the changes, rather than on the absolute numbers.
SFINX is used for two purposes: to calculate the origins of several selected 'problem flows', and to estimate the principle effectiveness of the intended pollution abatement options. Intended effects as well as unintended side-effects will be shown as a result of encompassing all flows within the system.

8.1.3 Nitrogen pollution problems in the EU and the related anthropogenic flows

Environmental problems related to nitrogen compounds
As stated in the introduction, nitrogen-related environmental problems can be detected on several scale levels.

The problem of groundwater contamination with nitrates (NO_3^-) is mostly placed on the local or regional level (RIVM, 1992). Surplus nitrate from agricultural soils, very mobile in soils and very soluble, leaches to the groundwater. In many areas in the EU, up to 25% of the EU territory, the maximum admissible concentration of 50 mg NO_3/l for drinking water is transgressed, making the water unfit for consumption without prior denitrification. Transgression of nitrate limits occurs in most if not all EU states, although the perception of its seriousness varies with the country (RIVM, 1992; Stringer, 1988; Strebel et al., 1989). The origins of the problem appear to be local, but for its effects this is not entirely true. In the long run, the nitrates accumulating in the groundwater will emerge somewhere. This may be after hundreds of years and at quite another location depending on groundwater flows, making the problem both long-term and transboundary (Zekster et al., 1992).

Acidification and eutrophication of natural areas occurs through atmospheric deposition of N-compounds (Hettelingh et al., 1991). As a result of deposition of acid and potentially acid compounds the soil pH drops, thus mobilizing aluminium and other metals, and causing a loss of vitality of trees and forests, and ultimately their death. As a result of nutrient addition, eutrophication causes a change in the species composition of ecosystems, favouring the earlier and faster growing species and supplanting the often more vulnerable and rare oligotrophic and mesotrophic species. This problem is defined on a continental scale (RIVM, 1992). Among its origins are the emission or evaporation of N-compounds (NO_x and NH_3, ammonia) from chimneys, exhaust pipes, stables and arable soils.

Eutrophication of coastal seas is caused mainly by the inflow of nutrients from rivers. This results in an increase in biomass. On the one hand, this allows for a larger fish population. On the other hand, increased nutrient availability may lead (and has already led) to toxic algal bloom, resulting in mass fish mortality. This problem might be referred to as occurring on a 'supra-fluvial' level (Busschbach et al., 1991). There is an ongoing discussion as to whether these effects are due mainly to nitrogen, to phosphorus or even to silicon, or in other words which macronutrient is the limiting factor. As yet, there is no clear answer to this question.

On the global level, N-compounds in the form of N_2O ('laughing gas') contribute to the global warming problem. N_2O has a Global Warming Potential (GWP) of 170-270 (Houghton et al., 1991), which means that one kg of N_2O emitted contributes 170-270 times more to the global

warming problem than one kg of CO_2. This compound is formed mainly during denitrification processes, especially in agricultural soils.

In the next section, an analysis is made of the nitrogen flows in the EU. In this way, a connection is made between the economic nitrogen flows and surpluses on the EU level, on the one hand, and some of the individual problems in the environment mentioned above, on the other.

The analysis of nitrogen flows within the EU economy and environment

Figure 8.1 presents the SFD for nitrogen compounds in the European Union for the year 1988. The EU's external borders form the boundary of the system, with one exception: the North Sea is also included in the system (boundaries following those of the Paris Commission). This has been done to enable comments to be made on the effects of the EU's nitrogen housekeeping on coastal seas.

All nitrogen compounds are included in this flow analysis except nitrogen gas (N_2), which forms 80% of the Earth's atmosphere and is therefore considered environmentally completely harmless. While nitrogen as an element cannot be degraded, nitrogen compounds can be reduced to nitrogen gas; in the SFD, this is classified as 'degradation'. Similarly, the generation of nitrogen compounds out of N_2-gas is considered an inflow item, and is classified as 'formation'.

As mentioned above, the SFD is the result of many economic and environmental processes. These are pictured in Figures 8.2a to 8.2e. To complete the SFD and the subdiagrams, data from many sources have been used (most important: Eurostat, 1990a, b and c; FAO, 1990; Ayres et al., 1989; Busschbach et al., 1991; Harenz et al. 1992; Huppes et al., 1992; Van Jaarsveld & De Leeuw, 1993; OECD, 1991; Olsthoorn, 1992 and 1993; Oslo and Paris Commission, 1992; Paris Commission, 1992; UN 1990a and b and many others (see Appendix 3)). Some of the missing data have been estimated by balancing every sector. Sometimes rather rough assumptions have been made, making some figures far less accurate than others. This is especially true for some of the environmental flows. Some flows even had to be omitted entirely, such as the extraction of nitrates with groundwater for drinking purposes and the formation and degradation of N_2O. However the magnitude of the figures is reliable, and in many cases this is quite sufficient to draw some relevant conclusions.

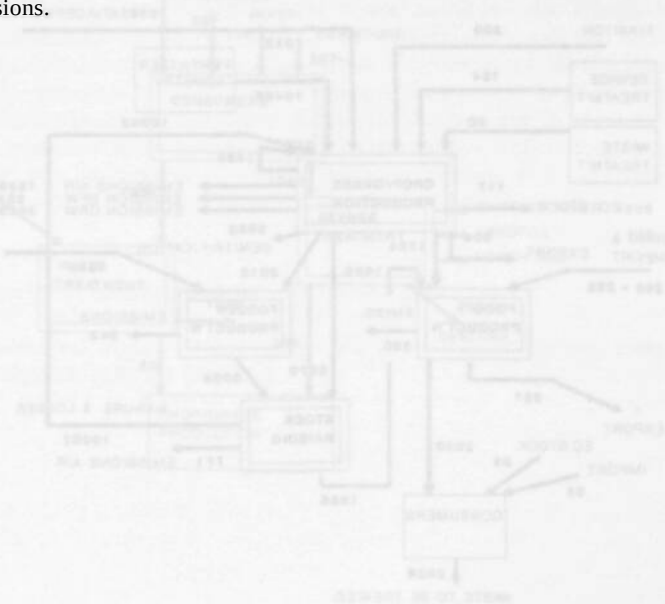
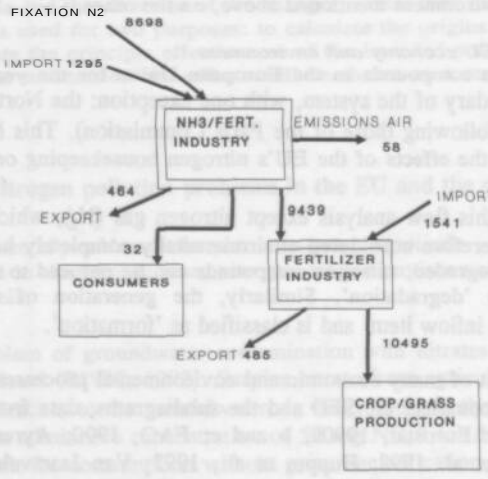
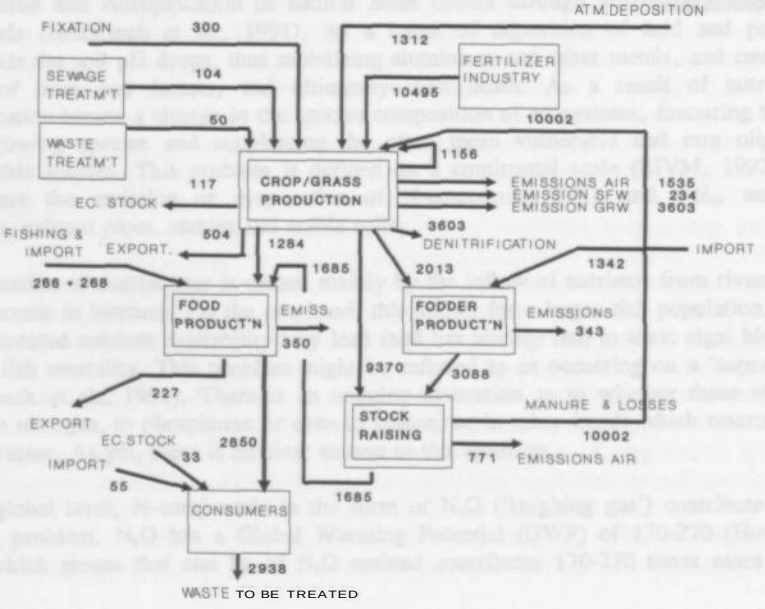


Figure 8.2 Suhdiagrams for the economic and environmental nitrogen flows within the EU. In ktonnes N, 1988.

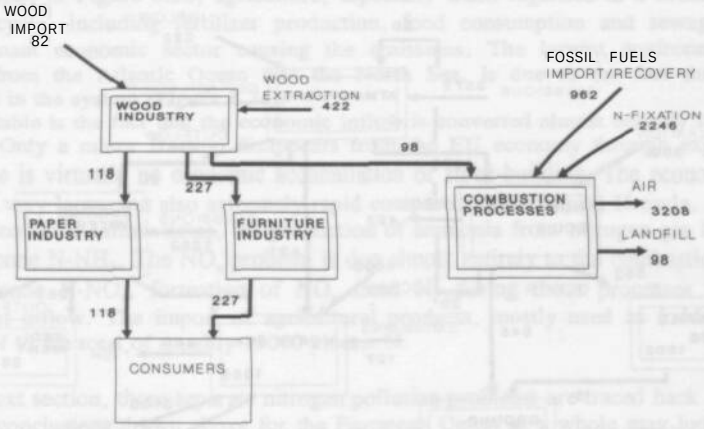
8.2a NH_3 and fertilizer industry



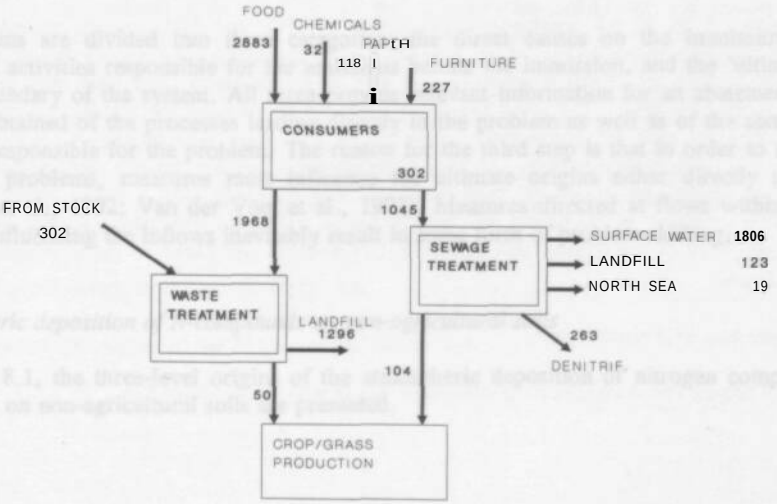
8.2b food production



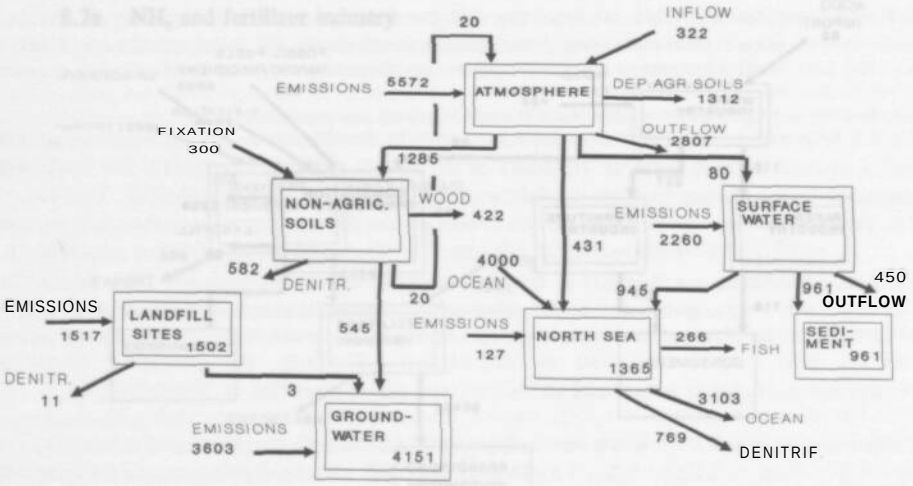
8.2c wood and fossil fuels



8.2d consumers and treatment of waste products



8.2e the environment



From Figure 8.1 it follows that the anthropogenic flows appear to be dominant for the environmental subsystem: over 90% of the environmental inflow originates from emissions. As can be seen in Figure 8.2b, agriculture, especially when regarded in a broad sense as the 'food supply cycle' including fertilizer production, food consumption and sewage treatment, is the predominant economic sector causing the emissions. The largest environmental 'inflow': the inflow from the Atlantic Ocean into the North Sea, is due to the fact that the North Sea is included in the system (Figure 8.2e).

Also notable is the fact that the economic inflow is converted almost entirely into emissions within a year. Only a minor fraction disappears from the EU economy through export or degradation, and there is virtually no economic accumulation or stock-building. The economic N-cycle is thus not only very large, but also extremely rapid compared to the natural N-cycle.

Of the economic inflow items, the production of ammonia from nitrogen gas is the largest: almost 8700 ktonne $N\text{-}NH_3$. The NO_x problem is due almost entirely to the combustion of fossil fuels. At 2246 ktonne $N\text{-}NO_x$, formation of NO_x from N_2 during those processes is the second most important inflow. The import of agricultural products, mostly used as fodder, contributes 1665 ktonne N to the total of roughly 15000 ktonne N.

In the next section, three separate nitrogen pollution problems are traced back to their origins. The general conclusions drawn above for the European Union as a whole may look different from the Point of view of the individual nitrogen-related problems.

8.1.4 Origins of three nitrogen-related environmental problems

In this section, the origins of three nitrogen problem flows are discussed:

- deposition of N-compounds on non-agricultural soils, leading to acidification and eutrophication of terrestrial ecosystems;
- nitrate leaching to groundwater, causing nitrate concentration limits to be transgressed;
- loading of the North Sea with N-compounds, leading to (toxic) algal bloom.

The origins are divided into three categories: the direct causes on the immission level, the economic activities responsible for the emissions behind the immission, and the 'ultimate origins' at the boundary of the system. All three provide relevant information for an abatement policy. A view is obtained of the processes leading directly to the problem as well as of the sectors that can be held responsible for the problem. The reason for the third step is that in order to truly resolve Pollution problems, measures must influence the ultimate origins either directly or indirectly (Huppes et al., 1992; Van der Voet et al., 1993). Measures directed at flows within the system without influencing the inflows inevitably result in some form of problem-shifting.

Atmospheric deposition of N-compounds on non-agricultural soils

In Table 8.1, the three-level origins of the atmospheric deposition of nitrogen compounds, NO_x and NH_3, on non-agricultural soils are presented.

Table 8.1 Origins of **atmospheric** N deposition on non-agricultural **soils** in **the** EU (in **kg.10^6** N/y, 1988)

Direct causes		
transboundary inflow of NO_x	**35**	3%
transboundary inflow of NH_3	25	2%
NO,-emissions within the EU	462	**36%**
NH_3-emissions within the EU	763	**59%**
TOTAL	1285	100%
Economic activities		
agriculture	738	57%
consumers and consumer waste treatment	65	5%
industry	88	7%
traffic	249	19%
power plants	79	6%
non-economic	66	5%
TOTAL	1285	100*
Ultimate origins		
NH, production from N_2	496	39%
import of NH_3/fertilizer	164	13%
import of food/fodder products	104	8%
import of wood	3	0%
import/recovery *of* fossil fuels	136	11%
NO_x formation from atm. N_2	315	24%
natural origins/transboundary inflow	67	5%
TOTAL	1285	100%

As can be seen, 57% of the atmospheric deposition of NO_x and NH_3 can be traced back to agriculture as the responsible sector. If we broaden this to the entire food supply and consumption cycle, we can include all of the consumers and pan of the industry, and state that the overall contribution is roughly 65%. The most important ultimate origins are the production and import of fertilizer, together with the involuntary formation of NO_x from atmospheric N_2 in combustion processes. Traffic and energy supply, together contributing 25%, are mainly responsible for this item. Import of agricultural products, used mostly as fodder, make only a minor contribution to the acidification problem, to the extent that this is due to nitrogen compounds. Again, we see the relative unimportance of the natural and transboundary sources compared to the economic sources inside the EU area.

Leaching of nitrates to groundwater

The origins of nitrate accumulation in groundwater are presented in Table 8.2.

Table 8.2 Origins of nitrate accumulation in groundwater in the EU (in kg.10' N/y, 1988)

Direct causes		
leaching from agricultural soils	3603	87%
leaching from landfill sites	3	0%
leaching from non-agricultural soils	545	13%
TOTAL	4151	100%
Economic activities		
agriculture	3729	90«
consumers and consumer waste treatment	35	1%
industry	122	3%
traffic	39	1%
Power plants	45	1%
non-economic	181	4%
TOTAL	4151	100«
Ultimate origins		
NH_3 production from N_2	2431	59«
import of NH_3/fertilizer	816	20«
import of food/fodder products	386	9«
import of wood	2	0«
import/recovery of fossil fuels	82	2«
NO_x formation from atm. N_2	196	5«
natural origins/transboundary inflow	238	6«
TOTAL	4151	100%

Leaching from agricultural soils (>85% of the groundwater load) can be traced back, as expected, almost entirely to agriculture as the responsible sector. Moreover, some of the leaching "0m non-agricultural soils is also due indirectly to the agricultural sector, through evaporation of NH_3 and deposition. Together, this indicates *90%* responsibility on the part of agriculture. The second largest contribution, at *4%,* is that from non-economic origins, i.e. natural fixation of N_2 and transboundary inflow. The other economic sectors make only a negligible contribution. Ultimately, no less than 79% comes from the import or production of fertilizer. Again, the import of agricultural products contributes in a minor way, as does the NO_x either formed from N_2 or recovered/imported with fossil fuels.

Inflow of nitrogen compounds into the North Sea

Table 8.3 shows the origins of the N load of the North Sea.

Table 8.3 Origins of the N load of the North Sea (in kg. 10^6 N/y, 1988)

Direct causes		
inflow from Atlantic Ocean	4000	73%
inflow from rivers	945	17%
atmospheric deposition	431	8%
direct emissions of wastewater	127	2\
TOTAL	SS03	100%
Economic activities		
agriculture	364	7%
consumers and consumer waste treatment	640	12%
industry	354	6%
traffic	91	2%
power plants	29	0%
non-economic	4025	73%
TOTAL	5503	100%
Ultimate origins		
NH_3 production from N_2	679	12%
import of NH_3/fertilizer	223	4%
import of food/fodder products	237	4%
import of wood	1	0%
import/recovery of fossil fuels	77	1%
NO_x formation from atm. N_2	184	3%
natural origins/transboundary inflow	4102	75%
TOTAL	5503	100%

For the North Sea, the picture is somewhat different. Some three-quarters of the N-load comes from the Atlantic Ocean and cannot be related to economic origins within the EU. This puts the scope for regulating the North Sea's nutrient budgets into a somewhat different perspective: three-quarters of the nitrogen load will remain anyway, and policy measures can only be directed towards influencing the anthropogenic quarter. However, the environmental problems occur mainly in the coastal areas, where the anthropogenic contribution is relatively larger.

Of this remaining quarter, the rivers contribute the most. Important sectors contributing to the riverine inflow are the consumers, due to surface-water emissions from sewage treatment works, followed by agriculture and industry. Food consumption, more than food production, contributes to pollution of the North Sea with nitrogen compounds. Ultimately, again two-thirds of the anthropogenic inflow originates in the import or production of fertilizer. The share of imported agricultural products is somewhat larger here. Not fodder, but food products determine this figure.

Conclusions

The direct causes of the three problem flows considered differ widely. Acidification is due to atmospheric deposition of NH_3 and NO_x; groundwater pollution originates in the leaching of nitrates, mainly from agricultural soils; for the North Sea, riverine inflow constitutes the largest anthropogenic inflow. The sectors responsible are the same for the three problem flows, though with varying contributions. Agriculture is the most important sector in two of the three cases; *foi* the North Sea households make the greatest contribution. In all three cases, the food production and consumption cycle as a whole predominates. Considering the ultimate origins, the import and production of fertilizer from N_2-gas is the main origin for all three problem flows. Measures

aimed at solving the problem flows must therefore affect at least this inflow, either directly or indirectly. Figures 8.3a and 8.3b give an overview of the relative contributions of the various sectors and ultimate origins of the three problem flows.

Not all nitrogen pollution problems are transboundary on the environmental side. However, they do have common economic origins: the food production and consumption cycle, and ultimately the import and production of fertilizer. Agriculture, its attendant industries and trade are organized on an international level, at least EU-wide. An EU-wide solution for these problems therefore seems to be indicated. In the next section, the focus is on policies and regulations with relevance for nutrient-related problems within the EU. Consideration is given not only to nutrient abatement Policies, but also to the Common Agricultural Policy (CAP). The CAP is mentioned in the literature as one of the major causes of nutrient problems (Atkin, 1993; Manale, 1991; Downs, 1991; Kramer, 1989; De Wit, 1988). Inevitably, therefore, it will have to be considered in the search for a solution.

8.1.5 Policies relevant for nitrogen flows

On various levels, policies are formulated to combat the negative impacts of excess nutrient losses to the environment. In most of the Northern EU states, there exist policies directed at manure. At a national level, too, most EU countries have acidification policies directed at NO_x and sometimes also at NH_3. National policies, international agreements made in conferences of the Rhine states and the North Sea states, and the EC's policy and especially the Nitrate Directive are discussed in the following sections.

Nutrient abatement policies are directed at solving the problems resulting from nutrient mismanagement. Nutrient management is influenced by economic policies, of which the agricultural policy is the most important. This policy is strongly dominated by the EC in its Common Agricultural Policy (CAP). Therefore, the CAP and the recent changes therein according to the so-called McSharry Plan will be treated also.

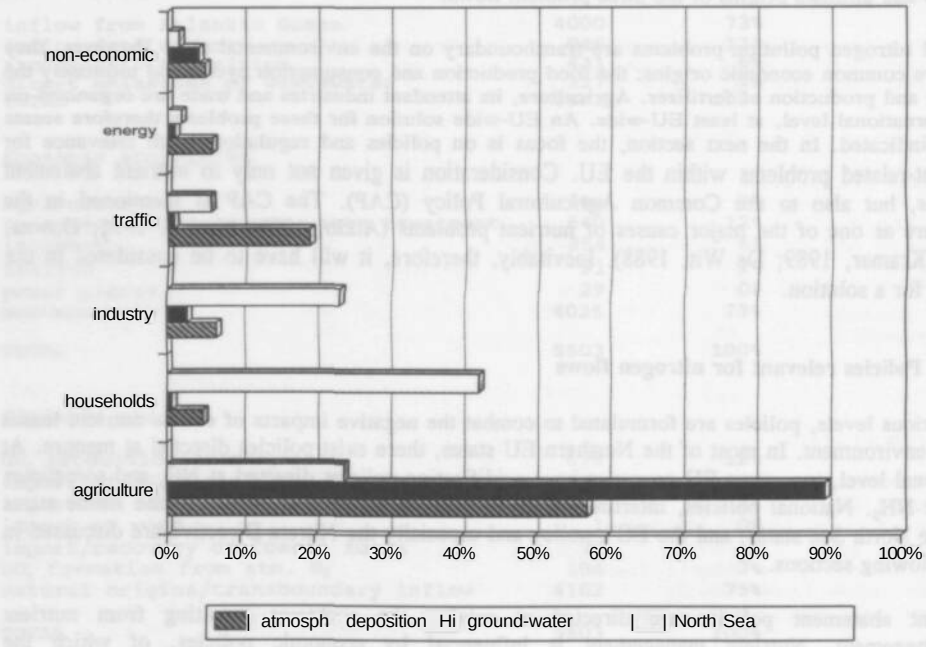
Nutrient abatement policies on a national level

Several member states, especially the Northern EU states, have recognized nutrient pollution Problems and have formulated their own nutrient policies. The contents vary widely (Noorduyn & Van Dijk, 1991). In all policies, targets have been defined for environmental quality (partly based °n EC directives) in terms of environmental concentrations. In most cases, though not all, these targets have been translated into emission levels. Variation between countries is mostly in the measures proposed and the policy instruments to implement these. In the UK, the only measure is the prohibition of manure discharges into surface waters. In Denmark, strict rules have been formulated for agricultural practice, including the prescription of all sorts of low-emission techniques and even an obligatory sowing of leguminous crops ('green manuring') to prevent l°sses from bare soils. In The Netherlands, policy is now shifting from maximum manure application standards based on P to a surplus tax based on a bookkeeping of minerals (N as well as P) by individual entrepreneurs (Ministry of Agriculture, 1993). In Germany and France, nutrient policies are delegated to the subnational level.

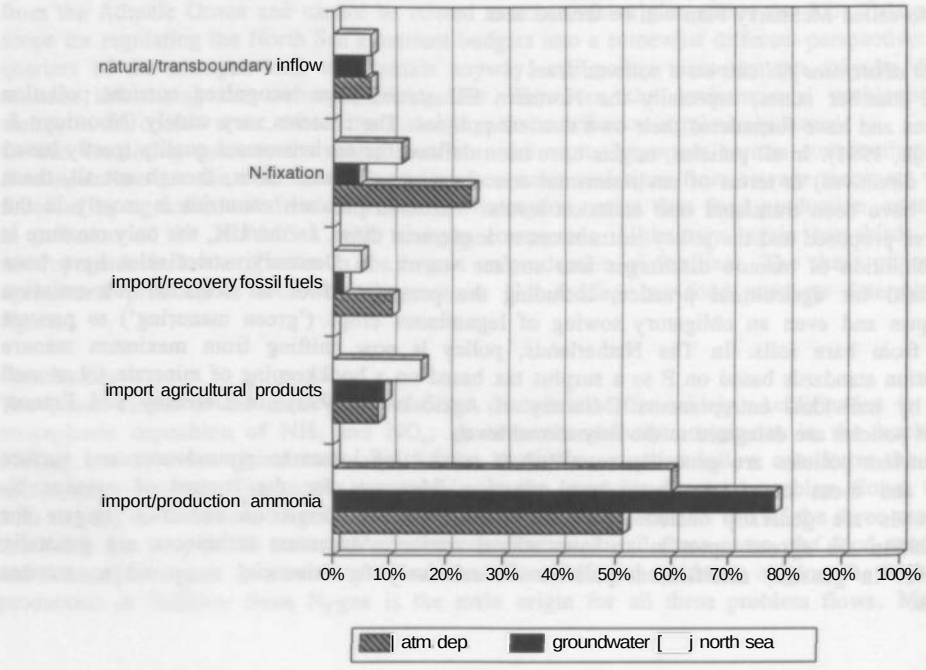
The nutrient policies are generally restricted to combatting losses to groundwater and surface water, and focus mainly on agricultural practice. Measures for the control of gaseous N-compounds are generally included in acidification policies. Emission reduction targets for acidification are agreed upon in an international setting. Abatement techniques are generally available. In general, acidification policies are relatively far advanced compared to nutrient policies.

Figure 8.3 Sectoral and ultimate origins of the three selected problems flows (%).

8.3a sectoral origins



8.3b ultimate origins.



International pollution control policies and agreements

In several international conferences agreements have been reached on nutrient targets:

The International North Sea Conference (INSC).

This conference was held for the first time in 1984; the participants are the environment ministers of the North Sea coastal states. At the first conference, the intention was laid down to protect the North Sea. At the second conference, it was decided that the (anthropogenic) N and P input to vulnerable areas would have to be halved between 1985 and 1995. North Sea states have agreed to combat nutrients in the effluent of water purification plants, to regulate the use of phosphate in detergents, and to reduce emissions from industrial and agricultural sources. At the third conference, in 1990, no additional nutrient policy was formulated (Ministerial declaration 1984, 1987, 1990).

Oslo and Paris Convention.

The Oslo Convention, 1974, has been ratified by most North-West European countries. It contains an agreement on marine pollution due to dumping from ships and aeroplanes. So far, this agreement has had little bearing on nutrification problems. In future, this might be otherwise.

The Paris Convention, 1978, is an agreement on the prevention of marine pollution from land-based sources. North Sea states as well as the EC have signed or ratified the treaty, in which the Parties have agreed to formulate programmes to combat this type of pollution, including both environmental target levels and measures. The Paris Commission (ParCom) has emerged from this convention. The ParCom also contains a Working Group on Nutrients, forming the platform for international deliberation and investigating possibilities for nutrient reduction. Extension of the sewage treatment grid, sewage water purification, sanitation of agricultural sources and sanitation of industrial sources are among the ParCom's proposals (Paris Commission, 1992; Oslo and Paris Commissions, 1992).

Rhine Action Programme (RAP).

The Rhine Action Programme has been agreed upon by the Rhine Bank States. For phosphates, there is agreement on a 50% reduction in immissions from anthropogenic sources in 1995 relative to 1985. Such sources include industrial discharges, sewage discharges and diffusive emissions from agriculture. No target has been set for N-compounds (International Commission for the Protection of the Rhine against Pollution, 1987).

Expectations are that, with the current developments, plans and commitments of the parties to these agreements, in 1995 the 50% immission reduction level will not have been realized for either the North Sea or the Rhine (Institute for Inland Water Management and Waste Water Treatment, 1992). Moreover, it is argued that in order to prevent a substantial loss of environmental quality a 50% immission reduction might not be sufficient, even if it is achieved (Anonymus, 1993). However, it is also stated that a 50% immission reduction is not only more than adequate to solve the problems, but would also have a severe negative impact on the North Sea's fish population (Boddeke, 1993). In fact, the scientific part of this debate has not yet been concluded.

EC acidification policy and EC nutrient policy

For acidification, the EC has adopted the concept of 'critical loads'. For each soil type and ecosystem combination, a critical load, i.e. a critical level of atmospheric deposition of acidifying substances, has been defined. The objective of the EC policy is to avoid transgression of these critical loads. As a step towards this goal, a stabilization of the emission level for NO_x in 1994 (relative to 1990) has been agreed on. For 2000, a 30% reduction is mentioned in the Fifth EC Environmental Programme. A further reduction may be agreed upon in the future. There are no

targets for NH_x; the setting of such targets is delegated to Member States, together with the choice and implementation of appropriate measures (Commission of the EC, 1992a). A scenario comprising a 60% emission reduction for NO_x and 40% for NH_3, leading to roughly 50% less atmospheric deposition of N-compounds, seems sufficient to solve most acidification-related problems in Europe (Scenario GLOBE II, RIVM, 1992) provided an additional emission reduction of 80% for SO_2 is realized. The total reduction in emissions of acidifying substances would then be roughly 70%.

The EC's nutrient policy consists of a Nitrate Directive (Council of the EC, 1991). The need for a phosphate directive is recognized in the Fifth Environmental Programme, but no initiatives have yet been undertaken in this direction. The nitrate directive is concerned mainly with groundwater. The guide level of 25 mg NO_3/l and the maximum admissible level of 50 mg NO_3/l have been adopted from the EC Drinking Water Directive and applied to groundwater. Regrettably, these concentration levels have not been translated into target immission levels. Although groundwater contamination with nitrate is defined on a local scale, a directive from the EC is needed in order to prevent unequal treatment of polluters. Apart from the environmental quality standards, the Directive comprises a course for action:

- Member States must identify vulnerable zones;
- Within these zones there must be
  * rules for slurry storage and application
  * maximum application rates for chemical fertilizers
  * rules for application techniques of chemical and organic fertilizers
  * record-keeping on overall agricultural activities.
- Member States must formulate Best Management Practices (BMPs) for agricultural practice. These BMPs may contain technical measures: restrictions on manure-spreading, manure application techniques, etc.

This Directive may offer scope for a nutrient policy on the EC level. However, as with the other international agreements, the formulation, implementation and control of measures is left to Member States. According to Manale (1992) it is extremely difficult to make directives both general enough to be applicable to the whole EC, and specific enough to offer solid building stones for national policies. Nevertheless, this Directive does offer openings for realization of a nutrient policy, and a rather strict one at that. Its implications for the agricultural sector could be far-reaching, but the economy/environment confrontation this implies is still to take place.

EC Agricultural policy

As concluded in the above, the food production and consumption cycle in general and the agricultural sector in particular are responsible for a major share of the wide variety of environmental problems relating to nitrogen compounds. For this reason the EC's agricultural policy, although not directed at nutrients as such, is of great importance for the nutrient flows within the EU.

The CAP comprises two main elements: price policy and structural policy. The structural policy is designed to create equal opportunities for farmers throughout the EU. The price policy aims to stabilize the market for agricultural products, guaranteeing farmers an acceptable income, consumers reasonable food prices and EC self-sufficiency. When prices drop below a certain level, the EC intervenes by buying large quantities of the product in question. The EC market is protected by means of import taxes on lower-priced products from outside its borders. Although this policy has clearly achieved its objectives, it has also created problems. The guaranteed prices have resulted in substantial overproduction, the cost to the EC is enormous, and market protection gives rise to continual disagreement in GATT negotiations. The high output of the agricultural sector has, as we concluded earlier, also created environmental problems within the EU.

The EC has recognized these problems. The Commission has produced a document called 'Development and Future of the Common Agricultural Policy', also known as the McSharry Plan after its instigator (Commission of the EC, 1991). The plan aims to solve the aforementioned Problems by establishing closer links with the world market. Guaranteed prices for cereals, milk and meat are to be lowered, for cereals even close to the current world market level. The loss of income will be compensated by an extra allowance per hectare. Fifteen percent of a farmer's acreage must be taken out of production on a rotational basis. With additional measures, some gain is intended for the environment: rewards for environmentally friendly management regimes, subsidies for switching from agriculture to timber production, and several other measures. While fte cost of the CAP to the EC remains undiminished, it is expected that the overproduction Problem will be somewhat alleviated. At the least, some scope is created for more environmentally friendly agricultural practice.

fe the next section, the consequences of the various policies for nitrogen flows in the EU will be evaluated.

8.1.6 Policies and nitrogen flows

To calculate the influence of existing and scheduled policies on nitrogen flows, the policy measures discussed above have been used as input for model calculations. To this end, a number °f assumptions had to be made:

1. All socio-economic factors (population size, state of technological development, consumption level, etc. etc.) remain unchanged compared to 1988.
2. Acidification policies will result in a 30% emission reduction for NO, (in accordance with the current EC target for the year 2000), and also a 30% emission reduction for NH_x, which is rather optimistic as no target level has set on the EC-level. These reductions are assumed to be achieved by technical means.
3. As an elaboration of the North Sea and Rhine States agreements, it has also rather optimistically been assumed that all households and all of the relevant industries will be connected to a sewage treatment plant, and that denitrification techniques will be adopted there with an effectiveness of 50%.
4. Under the terms of the Nitrate Directive, 10% of agricultural land will be designated as 'vulnerable zone', and in this area environmentally friendly techniques will be adopted for the application of manure and slurry, resulting in a 90% reduction of the evaporation of ammonia and more efficient uptake of these fertilizers by crops.

The changes in agricultural production anticipated as a result of implementation of the MacSharry Plan were to be included in the assumptions. However, the changes in pricing policy according to this plan are not expected to influence agricultural production levels to the extent of significantly changing nutrient flows. This possibly somewhat surprising conclusion is based mainly on a preliminary study by the Dutch Agricultural Economic Institute (LEI, 1991). Although the changes are most probably economically relevant, the crudeness of the analysis and of the data involved do not permit speculation on changes in agricultural practice; changes in production levels are around 1 %, going down for some products but up for others. Changes that may seem drastic from the point of view of combatting market surpluses, appear to be of minor importance for the EU's economic nitrogen regime as a whole. In other words, it is not so much overproduction, but regular 'self-supporting' agricultural production that causes the nitrogen-related environmental problems. No attempt has been made to comment on the costs of these measures, or on the problems with implementation that may or may not be expected.

Figure 8.4 The SFD for nitrogen compounds in the EU as a result of the scheduled policy regime. In ktonnes N/year, long-term equilibrium situation.

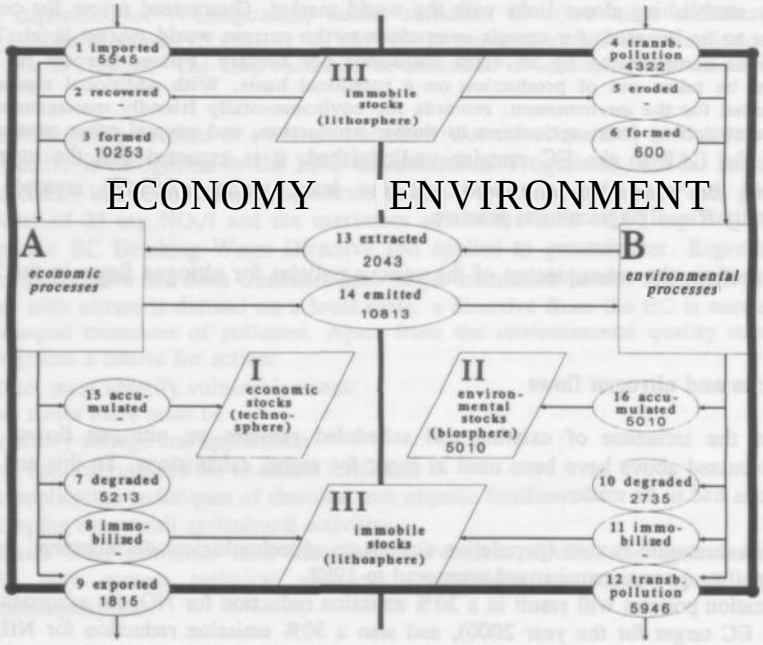


Table 8.4 Nitrogen flows in the EU as a result of internationally agreed or scheduled measures. Long-term steady-state situation, in ktonnes N/year and percentages.

	current regime	scheduled policy regime	relative change
Nitrogen budgets			
economic inflow	18789	17841	
economic outflow	5710	7028	
emissions	13079	10813	
- air	- 5572	- 4248	
- surface water	- 2260	- 1068	
- groundwater	- 3603	- 3674	
- landfill	- 1517	- 1824	
accumul. in env. 't	5478	5010	
- sediment	- 961	- 486	
- groundwater	- 4502	- 4525	
crop/grass production	14444	14293	
Environmental problem flows			
atm. dep. on non-agr. soils	1285	1058	(-18%)
leaching to groundwater	4502	4525	(+ 1%)
inflow to North Sea (excl. ocean)	1503	796	(-47%)

Figure 8.4 shows the SFD for the long-term steady-state nitrogen flows resulting from the aforementioned changes in the nitrogen regime. In Table 8.4, the figures are compared with the long-term steady-state nitrogen flows anticipated with a continuation of the present regime. These latter figures differ only slightly from the present situation because the economic nitrogen cycle is rather short: the life cycle for most nitrogen applications is completed within a year.

From Figure 8.4 and Table 8.4 it can be concluded that current and scheduled measures have a favourable impact on nitrogen management in the EU. On the whole, the economic inflow items in the SFD have decreased a little by the assumption of cleaner combustion processes, causing less formation of NO, from N_2. The economic outflow is higher as a result of increased 'economic degradation', due to the assumptions regarding denitrification in sewage treatment plant. A decreased inflow and an increased outflow result in an aggregate decrease in emissions, and therefore in greater economic efficiency of nitrogen use since all production remains practically at the same level. The efficiency of agricultural nitrogen use hardly seems to be influenced.

For the North Sea, the 50% immission reduction target is almost achieved. The measures themselves (and especially the assumption concerning sewage treatment) are therefore almost sufficient; there may still be implementation problems but these are not discussed here. The acidification problems will not be solved by a 30% emission reduction: a near-20% reduction in the atmospheric deposition of N-compounds is expected. We can detect two cases of problem-shifting: increased leaching to groundwater, leaving this problem flow unsolved, and more landfill, which in itself may not be problematical, but which will inevitably lead to greater nitrogen losses, mostly to the atmosphere and to the groundwater, on the local level. On the whole, the proposed policy measures do not satisfactorily solve all nitrogen-related problems, even if full implementation is assumed. This is not surprising if it is matched with the results of the origins analysis: the agricultural flows, including the use of fertilizer, are the main cause for the problems but are virtually unimpaired. Since the policy measures do not sufficiently influence the main origins of the problems either directly or indirectly, it is inevitable that a shifting of Problems will occur.

8.1.7 Conclusions and discussion

Environmental problems related to nitrogen compounds occur at various scale levels. These Problems have been treated as nitrogen budget problems and have been analyzed comprehensively. The technique of Substance Flow Analysis (SFA), implemented in the computer program SFINX, has been used for this analysis. By describing and modelling the EC as a system of interdependent nitrogen flows, is has proven possible to connect separate nitrogen related problems to their economic origins, and to estimate the effectiveness of certain abatement measures for those problems, as well as the shifting of problems that may occur.

Although the immediate causes of the separate nitrogen related problems vary a great deal, three selected problem flows can be traced back to the same ultimate origins. The atmospheric deposition of NO_x and NH_x, the leaching of nitrates to groundwater, and the anthropogenic input to the North Sea can all be attributed to the import and production of fertilizer.

The food production and consumption sectors can be viewed as the sectors most responsible for nitrogen-related problems. Although the problems occur on various scale levels, the most important causes are regulated on the EC level: the EC Common Agricultural Policy.

Measures and policies to combat nutrient-related problems are formulated by various Member

States as well as by various international bodies. The most important international measures are formulated in the EC Nitrate Directive, and in the INSC agreements and ParCom proposals for the protection of the North Sea. The changes in the CAP according to the McSharry Plan do not directly affect the agricultural nitrogen flows in a significant manner. The environmental problems are thus not so much related to overproduction, but to the CAP goal of self-sufficiency itself.

Most measures under the various existing policies and agreements are of a technical, end-of-the-pipe nature. If these are implemented adequately, two of the three selected problem flows are expected to decrease significantly but in neither case enough to solve the problem completely. The third problem flow, the leaching of nitrates to groundwater, will remain wholly unsolved. This is due to the fact that the most important origins, the nitrogen flows in agriculture and ultimately the addition of nitrogen to the system in the form of industrial fertilizer, are not significantly influenced.

To adequately solve all three nitrogen-related problems, therefore, other measures will be necessary, and are conceivable. This is the subject of Section 8.2 of this chapter, wherein both stringent technical possibilities and major changes in agriculture will be scanned on the implications for the environment and for society.

8.1.8 Summary

The EU is faced with major environmental problems related to nitrogen compounds. The origins of three such problems, the atmospheric deposition of N-compounds, the leaching of nitrates to groundwater, and the anthropogenic N-input to the North Sea, are investigated by means of a Substance Flow Analysis (SFA). Although the problems occur at various scale levels and have varying direct causes, the food production and consumption cycle can be appointed as the main responsible sector, and the production and import of fertilizer appears to be the major ultimate source in all three cases.
Measures to combat these problems have been agreed on in various international frameworks: the EC, the International North Sea Conference and the Rhine States conference. These measures include technical emission reduction for acidifying compounds resulting in a 30% emission reduction, extension of the sewage treatment network and application of denitrification with 50% effectiveness, and introduction of measures directed at efficiency increase and emission reduction in agricultural practice in 10% of the agricultural area. The recent changes in the CAP are not expected to lead to significant changes in nitrogen flows. Assuming full implementation, an almost sufficient 45% reduction is expected for the anthropogenic nitrogen flow into the North Sea. The atmospheric deposition of nitrogen compounds will be reduced by approximately 20%. The leaching of nitrates to the groundwater is expected to remain at the current level or even to increase a little. In all, these measures lead in the right direction but do not satisfactorily solve the three problems, mainly because the ultimate origins of the problems are not sufficiently influenced and measures therefore inevitably result in a shifting of problems.

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8.2 An economy-environment confrontation

8.2.1 Introduction

Major environmental problems arise within the European Union from the excessive use of nitrogen compounds. Among those are: acidification of forests and natural ecosystems through atmospheric deposition of N-compounds, eutrophication of inland waters and coastal seas mainly by organic N and nitrates, contamination of groundwater by nitrates, and a contribution to the global warming problem by dinitrogen oxide, N_2O. These problems occur at different scale levels, from local to global. In 8.1, the origins of three of these problems on the EU-level have been investigated by means of a Substance Flow Analysis (SFA):

(1) the atmospheric deposition of N-compounds on natural areas,
(2) the inflow of nitrogen compounds into the North Sea, and
(3) the leaching of nitrates to the groundwater.

It appeared that although the direct causes vary a great deal, the ultimate origins showed great similarity: the import and production of fertilizer was by far the most important origin in all three cases. In the abovementioned article, a package of several nitrogen pollution abatement measures as agreed on or considered in various international platforms was evaluated. Measures were taken from various environmental policies and agreements (Commission of the EC, 1992; ISNC 1984, 1987 and 1990; International Commission for the Protection of the Rhine against pollution, 1987) as well as from the Common Agricultural Policy (CAP) since its most recent changes (Commission of the EC, 1991). With the computer program SFINX, the effects of these measures on the nitrogen flows in the EC economy and environment were calculated. It was concluded that although the measures combined influence the three problem flows in the right direction, they do not provide a sufficient solution because the ultimate origins are not influenced adequately.

In section 8.2, several directions towards a solution of all three selected problem flows are explored. To gain an insight in the principle effectiveness of these directions, some extreme options are assessed: (1) a restriction on the import of agricultural products for fodder, (2) maximum application of technical measures, (3) termination of the use of chemical fertilizers, and (4) termination of the livestock production sector. Consecutively, some aspects of all these extreme options are combined in a compromise package of measures. Finally, the results of these calculations are discussed and conclusions are drawn.

8.2.2 Economic and environmental indicators

By means of a Substance Flow Analysis (SFA), the various abatement options are evaluated on their effectiveness for the three selected problem flows. The methods and data used and the computer program SFINX are described in Van der Voet et al. (1994). In order to evaluate the outcomes of the changes in flows resulting from those options, several *indicators* are defined and used as a reference. These must be indicative for the environmental problems caused by nitrogen compounds, but also for the economic functions fulfilled by these compounds: a general goal for each pollutant policy is to discard the environmental problems, while maintaining the functions. Because several options imply rather drastic changes in agriculture, it is important to comment on the economic consequences of the measures as well.

For the environmental problems, the aforementioned problem flows will serve as indicators. Changes in these flows are judged, if possible, by comparison with accepted environmental policy targets.

On the economic side, four indicators are chosen:

- the production level of crops and grass in terms of nitrogen;
- the agricultural efficiency of nitrogen use, calculated by dividing the sum of the agricultural outputs (export of agricultural products, output of EU-grown agricultural products to the food industry) by the sum of the agricultural inputs (import of agricultural products, industrial fertilizer, compost, sewage sludge and atmospheric deposition) * 100%;
- the economic efficiency of nitrogen use, calculated according to Huele et al. (1993): (1 - emissions/economic input) * 100%;
- EC agricultural self-sufficiency, again only in terms of nitrogen, obtained by calculating the ratio between nitrogen harvested in crop products and grass within the EU, and nitrogen in crop and grass required to feed the EU population, or (crop/grass production)/(crop/grass production + net import of agricultural products) * 100%.

With the aid of these indicators, the changes in nitrogen flows resulting from a package of abatement options are evaluated. Since the various indicators are not comparable, the evaluation is in qualitative terms. No attempt is made to range the options in an order of preference.

8.2.3 Reference values for the indicators

Environmental indicators

For atmospheric deposition of acidifying substances, the EC has adopted the concept of 'critical loads'. For each soil type and ecosystem combination, a critical load, i.e. a critical level of atmospheric deposition of acidifying substances, has been defined. The objective of the EC policy is to avoid transgression of these critical loads. As a step towards this goal, a stabilization of the emission level for NO_x in 1994 (relative to 1990) has been agreed on. For 2000, a 30% reduction is mentioned in the Fifth EC Environmental Programme. A further reduction may be agreed upon in the future. There are no targets for NH_x; the setting of such targets is delegated to Member States, together with the choice and implementation of appropriate measures (Commission of the EC, 1992a). A scenario comprising a 60% emission reduction for NO_x and 40% for NH_3, leading to roughly 50% less atmospheric deposition of N-compounds, seems sufficient to solve most acidification-related problems in Europe (Scenario GLOBE II, RIVM, 1992) provided an additional emission reduction of 80% for SO_2 is realized. The total reduction in emissions of acidifying substances would then be roughly 70%. In this article, a 50% reduction of the atmospheric deposition flow (NO_x and NH_3 together) is used as a 'target level'.

For the North Sea, the INSC target level of a 50% reduction in the combined riverine, atmospheric and direct immissions is adopted (Ministerial declaration, 1987 and 1990).

For groundwater, no such target level is defined or can be derived; evaluation of the effectiveness of measures must therefore be rather qualitative. Environmental standards are available for the nitrogen concentration in groundwater. A quantitative relation between the immission flow and the concentration cannot be established on the level of the EU as a whole. However, in a study for GLOBE (RIVM, 1992), scanning future developments for the environment in Europe, this relation is quantified: the immission/concentration ratio is specified for Europe on the level of grid cells measuring 75x75 km^2. The scenario 'GLOBE II' in this report contains measures reducing the stockbreeding sector to 85% and fertilizer use to 90%, with a higher uptake efficiency. The consequences of these measures for the area transgressing the 50 mg/l standard are given. By using these measures as an input for SFINX, the RIVM predictions concerning the environmental clean-up resulting from this scenario could be used as a reference for interpreting the results of the SFINX calculations. This reference should not be interpreted as a 'target', but as an indication of the problem-solving potential of a certain measure package. In Table 8.5, the environmental

indicators are given for the measures specified above. As we can see, the leaching flow has decreased by 15%. According to RIVM, under GLOBE II the area in which the SO mg/l nitrate concentration limit is transgressed decreases only slightly, from 25 to 20% of the EU area, while the area in which the 25 mg/l level is transgressed remains the same, at 70%. Changes of this order of magnitude cannot therefore be expected to solve the groundwater problem.

Table 8.5 Nitrogen flows in the EU resulting from the measures relating to fertilizer use fro» the GLOBE II scenario. Long-term steady-state situation, in ktonnes N/year and percentages.

	current regime	GLOBE II regime'	
Problem flows			
atm. dep. on non-agr. soils	1285	1194	(- 7%)
leaching to groundwater	4502	3823	(-15%)
inflow to North Sea (excl. ocean)	1503	1495	(- 1%)

'only the measures relating to fertilizer use

For the economic indicators, no target level can be designated, with the possible exception of EC agricultural self-sufficiency, for which 100% would seem optimum. For the agricultural and economic efficiency of nitrogen use, it would seem that the higher these figures are, the better. For crop/grass production no separate reference can be given.

8.2.4 Directions toward a solution of nitrogen related environmental problems

In this section, several possible directions will be investigated for solving the environmental problems related to nitrogen pollution. Four measures, or measure packages, will be evaluated with regard to their potential usefulness in relation to the signalled problem flows: the atmospheric deposition of acidifying nitrogen compounds on terrestrial ecosystems, the leaching of nitrates to groundwater, and the flows of nitrogen compounds into the North Sea.

As an initial measure, the impacts of an import restriction on agricultural products for fodder are calculated. The problem analysis (Van der Voet et al, 1994; Brandenburg et al., 1992) leads to the suspicion that this policy line will not lead to dramatic changes in the EU nitrogen budget. However, since this measure could be part of a larger package, it is important to assess its principle effectiveness.

The second line is based on a maximization of technical emission abatement measures. This line radicalizes the current EC policy line but preserves the current state of the agricultural sector as far as possible. The main goal here is to ascertain whether it is feasible to solve the environmental problems without affecting agricultural policy goals.

The other two policy lines are more radical still and would in fact imply an agricultural revolution. The third option proceeds from the assumption that the use of industrial fertilizer is the root of the problems. This opinion has followers in environmentalist circles as well as among scientists (Bohlool et al., 1992; O'Connell, 1992; Granstedt, 1992); it also follows from the problem analysis presented in Van der Voet et al. (1994), where the import and production of fertilizer is identified as the main ultimate origin of all three problem flows. The extreme solution in this case is to refrain from using industrial fertilizer at all.

The fourth option is equally drastic, but starts from the basic assumption that the problems arise mainly from the stockbreeding sector. It is argued that the use of animal manure inevitably causes large losses of nutrients to the environment (Ministry of Agriculture, 1993; Huppes et al, 1992;

but also concluded by Baker & Senft, 1992). Although ultimately these flows can be traced back to industrial fertilizer, the inefficiency of stockbreeding processes causes the real problems by creating a need for such a high input (Isermann, 1993). In this policy line, the most drastic solution is to close down the entire stockbreeding sector throughout the EU. It goes without saying that neither of these last two options constitutes a realistic scenario; however, they are included to gain an insight into the maximum possible consequences of such policy lines.

Finally, an attempt is made to combine some of the most promising options from all four lines in one 'optimum measure package', aimed at finding a compromise between agricultural and environmental policy goals.

8.2.5 'Putting and end to the EU's expansion of its agricultural territory'

It has been frequently stated by environmental activists as well as scientists that the import of agricultural products such as manioc, soy and others for the purpose of feeding cattle is not only immoral, but is also one of the main causes of the overproduction of manure within the EU and its concurrent environmental problems. In this section, the impacts of an import restriction for the EU as a whole are evaluated. Assumptions are:

1. Socio-economic factors remain unchanged.
2. The import of fodder crop (1342 ktonnes of N) is terminated completely.

Three alternatives have been elaborated. In alternative 1, the loss of fodder materials is compensated by higher fodder crop production within the EU. Without further measures, this would appear to be the most likely development. In alternative 2, the loss is partly compensated by higher crop production within the EU, and partly by cutting crop exports. This also implies a slight change in the choice of crops. In the third alternative, there is no compensation at all, which results in a concurrent shrink of the stockbreeding sector (as it happens, by 15%). In Table 8.6, the impacts of the various alternatives on the economic and environmental indicators are presented. Additional information can be found in Table 8.11.

Table 8.6 Nitrogen flows in the EU as a result of terminating fodder imports. Long-term steady-state situation, in ktonnes If/year and percentages.

	current regime	restricted import alt. 1		alt. 2	alt. 3
Environmental indicators					
atm. dep. on non-agr. soils	1285	1315	(+2%)	1269	1206
leaching to groundwater	4502	4560	(+1%)	4529	4113
infl. to N. Sea (excl. ocean)	1503	1514	(+1%)	1470	1388
Economic indicators					
crop/grass production	14444	15795	(+9%)	15064	13797
agric. efficiency (N)	25.2%	24.9%	(-0%)	22.8%	26.0%
econ. efficiency (N)	30.4%	30.1%	(-0%)	28.8%	29.3%
EC self-sufficiency (N)	94.4%	102.6%	(+8%)	100.1%	101.5%

At the EU level, the import restriction does not appear to make a great difference. Any difference there is seems to be unfavourable, due to the assumption that compensating crop production will take place on EU acreage. This does not mean that on lower scale levels there might not be a change for the better. This measure may work out well in areas with a high concentration of livestock, but in the EU-wide analysis it is impossible to verify such a conclusion.

The various alternatives do not differ much in their results. Only the option of import restriction without any compensation, thus implying a shrink of the stockbreeding sector, has an impact that, however slight, goes in the right direction. The option of decreasing the stockbreeding sector will be treated separately.

8.2.6 'Technology all the way'

A maximization of technical measures ('techmax') is most in line with current policies and agreements. It is the ultimate way of trying to conform to environmental standards without having to give up any economic values. The main aim here is to close the leaks in the economic system or, in other words, prevent emissions. The assumptions that have been made in order to assess the consequences of this policy line are:

1. Socio-economic factors remain unchanged.
2. Agricultural output remains on the same level as under the current regime.
3. Technical measures will reduce all NO_x emissions as well as industrial and stable NH_x-emissions to the atmosphere by 90%.
4. As much as 25% of the EU's animal manure is assumed to be collected and subjected to centralized manure treatment. In the process, animal manure is assumed to be transformed into an organic fertilizer that can be used with the same efficiency as industrial fertilizer (Booij & Van der Hoek, 1992).
5. The organic fertilizer is assumed to be used within the EU, replacing industrial fertilizer to a level in accordance with current output levels. The production of industrial fertilizer is assumed to drop accordingly, keeping import and export at the 1988 level.
6. The other 75% of animal manure is assumed to be applied in such a manner that the efficiency of N-uptake by crops or grass will increase significantly, and ammonia emissions will drop accordingly.
7. All industries and all households will be connected to a sewage treatment system; denitrification of the influent will take place with an effectiveness of 70%.

In Table 8.7 the consequences of these assumptions for EU nitrogen flows are given. Further information is available in Table 8.11.

Table 8.7 **Nitrogen flows in the EU as a result of maximized technical emission reduction measures. Long-term steady-state situation, in ktonnes N/year and percentages.**

	current regime	techmax regime	
Environmental indicators			
atm. dep. on non-agr. soils	1285	383	(-70%)
leaching to groundwater	4502	3785	(-16%)
inflow to North Sea (excl. ocean)	1503	298	(-80%)
Economic indicators			
crop/grass production	14444	14444	(n.c.)
agricultural efficiency (N)	25.2%	30.7%	(+ 6%)
economic efficiency (N)	30.4%	50.7%	(+20%)
EC self-sufficiency (N)	94.4%	94.3%	(- 0%)

As was expected, the effects of this technical measure package are in the same direction as those achieved with the scheduled policy measures, but more pronounced. The total inflow to the economy is significantly diminished, due mainly to a reduction in fertilizer production. This is the result of assumptions 4 and 5 with regard to centralized manure treatment. The economic outflow

has increased compared to the current regime, although not so much as under the proposed policy measures regime. The economic efficiency of nitrogen use, also in agriculture, is much better, and emissions are therefore almost halved. Because of the decrease in fertilizer use, the level of fertilizer production has dropped. On the other hand, a quite substantial secondary or recycling industry has been set up: for centralized manure treatment.
A shifting of problems has occurred, although less so than under the 'scheduled measures' regime, from emissions to air or surface water to landfill, in turn leading to a slightly higher secondary emission to the atmosphere and to groundwater.

For the selected problem flows, the 'techmax' package works out favourably. North Sea anthropogenic inflow stabilizes at 20% of the current level, much lower than the agreed 50%. Atmospheric deposition on non-agricultural soils drops by 70%. Again, this is more than the 50% required overall, but to draw any conclusions with respect to transgression of critical loads the measures must be specified on a more local level. The leaching of nitrates to groundwater decreases by 16%, to 84% of the current level. Under the GLOBE II assumptions, nitrate leaching decreased by 15%. Since GLOBE II is not expected to result in sufficient clean-up of the groundwater, this measure package will likewise be insufficient to prevent concentrations rising above the level of 50 mg NO_3/l, as demanded in the Nitrate Directive. Two of the three selected problem flows could be solved more than adequately, as it appears, by stringent technical measures. For the third one, groundwater, other measures seem to be indicated. Since this problem flow originates to 90% from agriculture, these measures must involve major changes in the agricultural sector. In the next sections, this will be elaborated.

8.2.7 'Let's blame it on the fertilizer'

Ultimately, all three problem flows can be traced back to the production and import of fertilizer. An extreme approach to investigating and testing the effectiveness of measures in this direction is to assume complete termination of all industrial fertilizer use. Agriculture would then be totally dependent on animal manure, as it was some hundred years ago, and as it is currently practised under some alternative agricultural regimes. In Table 8.8 the outcome of this measure is presented. The assumptions are:
1. Socio-economic factors remain unchanged.
2. Import, export, production and use of fertilizer are down to zero.
3. Import of agricultural products for food by the food industry is increased to the level needed to feed the EU population its current amount of nitrogen; no specification is made as to which agricultural products are involved.

Table 8.8 Nitrogen flows in the EU as a result of terminating the use of industrial fertilizer. Long-term steady-state situation, in ktonnes N/year and percentages.

	current regime	no fertilizer	
Environmental indicators			
atm. dep. on non-agr. soils	1285	667	(-48%)
leaching to groundwater	4502	1208	(-73%)
inflow to North Sea (excl. ocean)	1503	1052	(-30%)
Economic indicators			
crop/grass production	14444	1771	(-88%)
agricultural efficiency (N)	25.2%	23.3%	(- 2%)
economic efficiency (N)	30.4%	16.2%	(-14%)
EC self-sufficiency (N)	94.4%	33.2%	(-61%)

Additional information on nitrogen budgets is presented in the overall comparison table, Table 8.11. As can be concluded from Tables 8.4 and 8.7, the nitrogen throughput decreases substantially under this measure: all nitrogen 'book-keeping' items (especially economic formation) are significantly lower than under the current regime. This measure apparently represents real 'at-source abatement'. As a consequence, losses to the environment are also much smaller. However, if we take a look at the problem flows, we see that for two out of three of them this measure works out less satisfactorily than the option with maximum application of technical measures. For the groundwater problem, still unsolved with the 'techmax' approach, this no-fertilizer measure is indeed effective: leaching is reduced by 73%. Emissions to the atmosphere are decreased by 34% only, and the remainder is dominated by NO_x-emissions that are not influenced by measures aimed at agriculture. However, since the transboundary outflow of NO_x is high compared to that of NH_x, and measures to reduce ammonia emissions are thus more effective within the EU, the deposition reduction target of 50% is almost reached all the same. Inflow to the North Sea is reduced by 30% only. The bulk of the remaining emissions to surface waters is due to sewage treatment effluent.

A striking detail in Table 8.8 is the very small figure for crop/grass production. Through the loss of fertilizer, agricultural output would be reduced to a 19th century level of about a tenth of current output if no compensatory measures were taken. With the 1988 population, this would mean that three-quarters of the (nitrogen in) food products must be imported from outside the EU. The remaining import figure, 4662 ktonnes N, is therefore dominated by food products. In fact, this measure would imply that the EU population becomes largely dependent on non-EU countries for its food supply, and it is therefore contrary to the present CAP goal of EC self-sufficiency. This measure would mean the export of agriculture, with its concurrent environmental problems.

8.2.8 'A Union of veganists"

A different but equally draconic solution to the environmental problems related to nitrogen compounds can be formulated on the assumption that the stockbreeding sector is responsible for the problems. The reasoning behind this is that the environmental losses from manure and slurry cannot be sufficiently controlled, and will inevitably remain much larger than losses from industrial fertilizer. What would happen, then, if all animal manure and slurry were to disappear and with it, as a matter of course, all livestock? The results of terminating the livestock production sector are presented in Table 8.9, and additionally in Table 8.11. The assumption then is that not only the production, but also the consumption of animal products are totally discontinued. This therefore implies not only an agricultural revolution, but also a consumers revolution. The assumptions are:

1. Socio-economic factors remain unchanged.
2. All flows with regard to import, production, export and consumption of fodder crops, fodder, grass and animal products are down to zero; the stockbreeding and fodder industry have disappeared.
3. As explained below, fertilizer use is lowered to the level needed to feed the 1988 EU Population its 1988 amount of nitrogen.

Table 8.9 Nitrogen flows in the EU a« a result of terminating the entire stockbreeding sector. Long term steady-state situation, in ktonnes N/year and percentages.

	current regime	no livestock	relative
Environmental indicators			
atm. dep. to non-agr. soils	1285	536	(-58%)
leaching to groundwater	4502	918	(-80%)
inflow to North Sea (excl. ocean)	1503	1057	(-30%)
Economic indicators			
crop/grass production	14444	3292	(-77%)
agricultural efficiency (N)	25.2%	76.9%	(+51%)
economic efficiency (N)	30.4%	22.1%	(- 8%)
EC self-sufficiency (N)	94.4%	100.4%	(+ 6%)

An important aspect of terminating livestock production is the increase in agricultural efficiency, which is boosted from 25% to more than 75%. In the present situation, in terms of nitrogen more than three-quarters of crop/grass production is intended for livestock, while less than 15% of this ends up in food products. Without livestock, maintaining the same harvest level in terms of nitrogen, with all grass replaced by crop, therefore leads to an overproduction of 300%. Maintaining the current rate of fertilizer application would lead, even without the animal manure, to an overproduction of more than 100%. In this measure package, therefore, fertilizer use is adapted to the nitrogen needs of the EU population; it leaves the food supply as well as the export of food products at the 1988 level in terms of nitrogen. The disappearance of livestock production is thus linked to a major reduction in fertilizer use. The stockbreeding sector can therefore indeed be held responsible for a large part of the problem, not so much because of the losses from manure and slurry, but because the intrinsically very inefficient use of nitrogen in this sector makes it necessary to keep up such a high vegetative production level with a concurrent high level of fertilizer use.

The impacts of this measure on the environmental problems are therefore rather similar to those of the no-fertilizer option: a de-intensification of the economic cycle with a concurrent decrease of emissions. Leaching to groundwater decreases even more than under the no-fertilizer regime. Atmospheric deposition is reduced by even more than 50%. The North Sea load decreases by 30%, however.

On the societal side, EC self-sufficiency is guaranteed in this case. Realization of an entirely veganistic EU is just as unlikely as the previous scenario, however, and would affect the agricultural sector in many imaginable and unimaginable ways.

8.2.9 'Running with the hare and hunting with the hounds'

Figures 8.5 and 8.6 and Table 8.11 summarize the effects of the various packages of measures specified above on the environmental and economic indicators.

Figure 8.5 Effects of the various measure packages on the environmental indicators. In %, current situation = 100%.

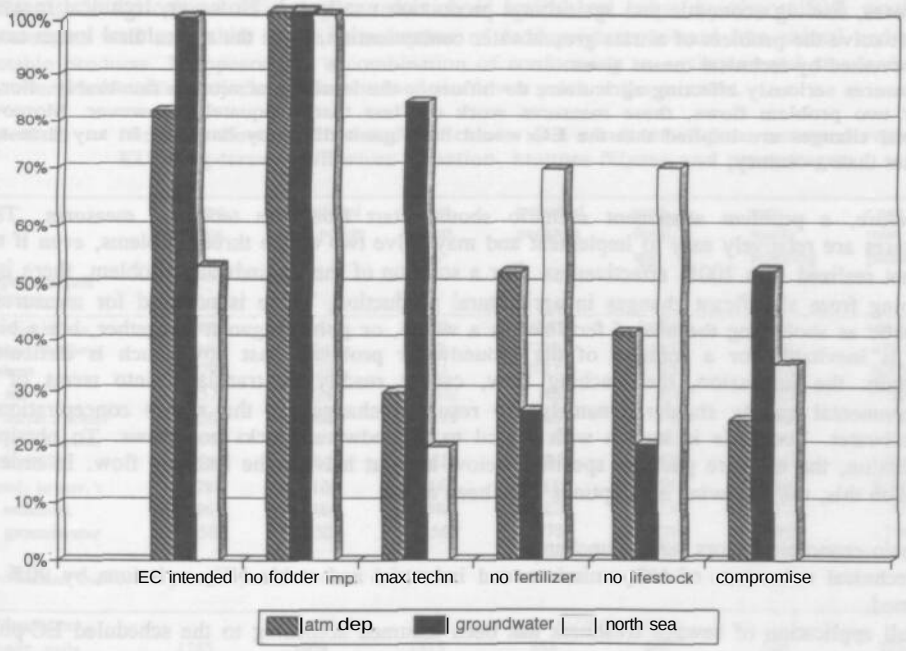
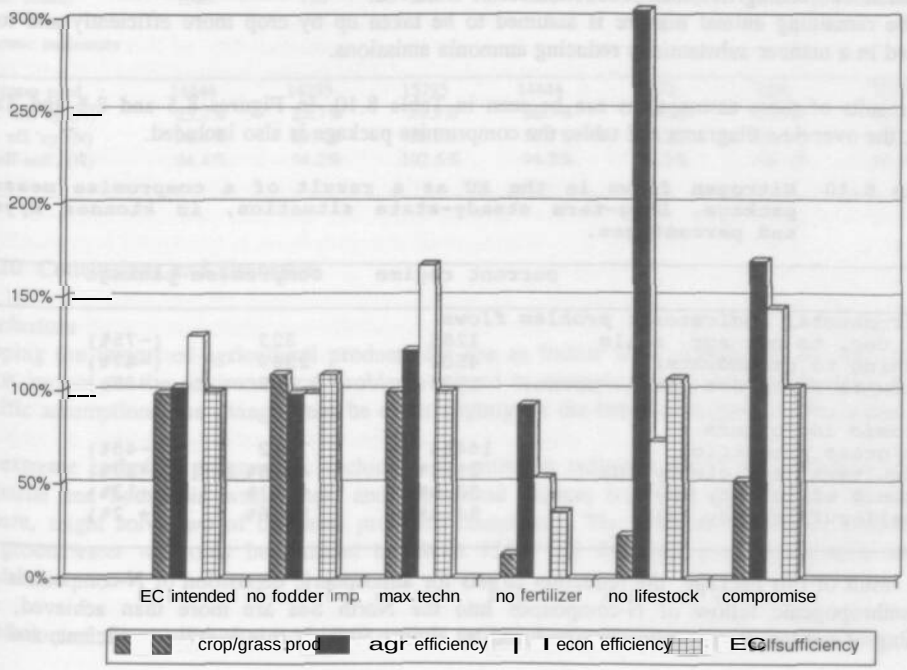


Figure 8.6 Effects of the various measure packages on the economic indicators. In %, current situation = 100%.



From Figures 8.5 and 8.6, several conclusions can be drawn:

- The North Sea and the atmosphere can be cleaned sufficiently by technical emission abatement measures, leaving economic and agricultural production unaffected. However, technical measures cannot solve the problem of nitrate groundwater contamination, since the agricultural losses cannot be prevented by technical means alone.

- Measures seriously affecting agriculture do influence the leaching of nitrates favourably. For the other two problem flows, these measures work out less than adequately, however. Moreover, societal changes are implied that the EC would have great difficulty handling in any time span shorter than a century.

Therefore, a problem abatement scenario should start from the technical measures. These measures are relatively easy to implement and may solve two of the three problems, even if they are not realized with 100% effectiveness. For a solution of the groundwater problem, there is no escaping from significant changes in agricultural production. There is no need for measures as dramatic as abolishing the use of fertilizer as a whole, or going veganist altogether, but a bit of both is inevitable for a solution of the groundwater problem. Just how much is difficult to ascertain: the immission, the leaching flow, cannot readily be translated into terms of the environmental quality standard, namely the resulting changes in the nitrate concentration of groundwater. Too little is known with regard to groundwater stocks and flows. To obtain an impression, the measure package specified below aims at halving the leaching flow. In order to establish this, the following assumptions have been made:

1. Socio-economic factors remain unchanged.
2. Technical reductions of NO_x-emissions and industrial and stable NH_x emissions by 90% are assumed.
3. Full application of sewage treatment has been assumed according to the scheduled EC-policy package.
4. Application of chemical fertilizer is reduced to 60% of the current level.
5. The stockbreeding/livestock production sector is halved.
6. The remaining animal manure is assumed to be taken up by crop more efficiently and to be applied in a manner substantially reducing ammonia emissions.

The results of these assumptions can be seen in Table 8.10. In Figures 8.5 and 8.6 and Table 8.11, the overview diagrams and table, the compromise package is also included.

Table 8.10 Nitrogen flow* in the EU as a result of a compromise measure package. Long-term steady-state situation, in ktonnes N/year and percentages.

	current regime	compromise package	
Environmental indicators: problem flows			
atm. dep. to non-agr. soils	1285	323	(-75%)
leaching to groundwater	4502	2369	(-47%)
inflow to North Sea (excl. ocean)	1503	529	(-65%)
Economic indicators			
crop/grass production	14444	7512	(-48%)
agricultural efficiency (N)	25.2%	42.6%	(+17%)
economic efficiency (N)	30.4%	43.7%	(+13%)
EC self-sufficiency (N)	94.4%	96.6%	(+ 2%)

As a result of this package, the reduction targets for atmospheric deposition of N-compounds and the anthropogenic inflow of N-compounds into the North Sea are more than achieved, and leaching of nitrates to groundwater is reduced by almost 50%. If this is still insufficient, and that

is something that cannot be ascertained at the present moment, then at least it represents a great step forward. Still, the changes implied in this measure package are by no means negligible. Apart from a rise in agricultural efficiency, a reduction of agricultural output by almost 50% would be indicated, as well as a shift in the consumption of food products toward less animal and more vegetable products. It appears that a combination of conforming to environmental standards and agricultural self-sufficiency cannot be obtained at a lower price at the moment.

Table 8.11 Nitrogen flows and related indicators as a result of various assumed regimes. EU, long-term equilibrium situation, ktonnes N/year and percentages.

	current regime	scheduled EC policy	fodder import restr.	technical package	zero fertil. use	zero stock-breeding	compro-mise package
Nitrogen budgets							
economic inflow	18789	17841	18850	14243	9056	9052	10830
economic outflow	5710	7028	5669	7222	1463	1999	4731
emissions	13079	10813	13181	7021	7593	7053	6099
- air	- 5572	- 4248	- 5602	- 1020	- 3671	- 3279	- 884
- surface water	- 2260	- 1068	- 2278	- 467	- 1753	- 1816	- 1070
- groundwater	- 3603	- 3674	- 3656	- 3123	- 615	- 388	- 1761
- landfill	- 1517	- 1824	- 1517	- 2411	- 1506	- 1508	- 2389
accumul. in env.'t	5478	5010	5544	4011	1958	1690	2839
- sediment	- 961	- 486	- 984	- 226	- 750	- 772	- 471
- groundwater	- 4502	- 4525	- 4560	- 3785	- 1208	- 918	- 2369
Environmental indicators: problem flows							
atm. depos. on non-agr. »oils	1285	1058	1315	383	667	536	323
leaching to gr. water	4502	4525	4560	3785	1208	918	2369
inflow to North Sea (excl. ocean)	1503	796	1514	298	1052	1057	529
Economic indicators							
crop/gnu« prod.	14444	14293	15795	14444	1771	3292	7512
agric. eff.'cy (N)	25.2%	25.7%	249%	30.7%	23.3%	76.9%	42.6%
econ. eff.'cy (N)	30.4%	39.4%	30.1%	50.7%	16.2%	22.1%	43.7%
EC self-suff. (N)	944%	94.2%	102.6%	94.3%	33.2%	100.4%	96.6%

8.2.10 Conclusions and discussion

Conclusions

Stopping the import of agricultural products for use as fodder from outside the EU has only a minor impact on the environmental problems related to nitrogen compounds. Depending on the specific assumptions, the changes may be either slightly for the better or slightly for the worse.

An extreme technical programme, including air emission reduction by 90%, treatment for all industrial and household wastewater, and centralized manure treatment for 25% of all animal manure, might solve two of the three problems completely. The problem of nitrates leaching to toe groundwater will only be reduced by about 15%, and therefore probably remain largely unsolved.

Resolution of the groundwater problem requires radical measures in the agricultural sector. Two

possible directions have been scanned by calculating the impacts of two extreme policies: (1) returning agriculture to the pre-fertilizer age by banning the use of fertilizer, and (2) increasing agricultural efficiency in the only radical way possible by eliminating livestock production altogether. Both options seem effective: the first through reducing the agricultural nitrogen cycle as a whole to a tenth of its current throughput, and the other by tripling agricultural efficiency. Both options reduce nitrate leaching to groundwater to approximately 20% of the current level. However, the implications of such extremes for society would be severe. In the one case, agricultural output is reduced to a tenth of the current level as well, making the EU largely dependent on imported food. In the other case, the adoption of a completely veganistic lifestyle by the EU population is implied. Apart from that, major parts of the agricultural sector would disappear in both cases.

To solve all three problem flows, an abatement package comprising both technical measures and major agricultural changes is required. Such a package would be less drastic than the extreme options mentioned above, but would still involve radical interventions in agricultural practice.

Discussion

Nitrogen compounds, although they cause environmental problems, fulfil an indispensable function as nutrients. The production and consumption of food is the cause of the environmental problems: as long as the current EU population is fed with the current EU agricultural products, at least the problem of groundwater pollution with nitrates appears to be inevitable.

Developing a solution for these problems within the EU is an example of an unavoidable clash between the economy and the environment. Atmospheric deposition of N-compounds and the anthropogenic N-input to the North Sea might be solved by technical means. For these problems it is a mere question of being prepared to pay a certain amount of money, an argument that might even be won by the environmental side. Cleaning up the groundwater is another matter, however, and implies changing the whole nature of food production and consumption. To solve this problem, the EU must live partly on imported food, thereby in point of fact expanding its effective area and exporting its environmental problems. The other approach is to reduce the consumption of animal products substantially in the name of sustainability; of this option it can be stated in its favour that at least the EU population would be keeping its problems to itself. There seems to be little scope for less radical scenarios.

It is then a question of choice: do we choose to solve the problems to the degree laid down in the various agreements, or do we choose to keep food production and consumption more or less as they are at present? In the past, we have come to accept the fact that we cannot drink untreated surface water as a consequence of the pollution level that goes hand in hand with a population of our size. Now, we may choose to accept having to purify groundwater before using it as drinking water rather than abolishing agriculture as we know it. For the present, any proposal for increasing the environmental quality standard level of 50 mg nitrates/1 groundwater would represent an arguable case. For the future however, with an ever-growing world and EU population, the changes in agricultural style and food patterns described above might have to be reconsidered. If a substantial increase in the efficiency of agricultural nitrogen use by technical means remains impossible, such changes may constitute the only option for solving the environmental problems of the future.

8.2.11 Summary

In a previous article, the origins of three separate environmental problems related to nitrogen

compounds, the atmospheric deposition of N-compounds have been investigated by means of a Substance Flow Analysis (SFA). In all three cases, the production and import of fertilizer has come up as the major source. A package of internationally agreed or intended measures leads in the right direction but does not satisfactorily solve the three problems. In order to obtain a picture of the changes in the anthropogenic nitrogen flows needed for a solution, the effectiveness of several more radical interventions is calculated.
A selection of rigorous technical measures is expected to reduce the atmospheric deposition of N-compounds to a level that seems acceptable for the EU as a whole, and will reduce the anthropogenic input of N-compounds into the North Sea well below the agreed level of 50% of the present load. The third problem, the pollution of groundwater with nitrates, would still be unsolved.
Resolution of this last problem requires very radical changes in the agricultural sector, reducing agricultural output substantially. Two directions are explored by assessing the impacts of the extremes: the terminating of industrial fertilizer use to combat the problems at the source, and the abolishing of the entire stock breeding sector to radically increase the agricultural efficiency. These changes do contribute to a solution of the groundwater problem, but imply either greater dependence on imported food, or a major change in food consumption patterns, from animal toward vegetable products. Providing the current EU population with its present diet is simply not compatible with the absence of environmental problems. The question then arises, how does acceptance of the draconic measures required to solve an environmental problem weigh up against acceptance of the fact of having to cope with contaminated groundwater.

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CHAPTER 9 EVALUATION OF THE CASE STUDIES

9.1 Introduction

As stated before, applying in practice a theoretically developed methodology serves various purposes. In the first place, there is feedback to the methodology development itself: practical applications force one to take every step in a calculated way. During the research for this thesis, this confrontation of theory with practice has led to several general conclusions regarding the *quantification* step of the SFA framework. This concerns data availability and quality on the one hand, and the translation of a bookkeeping overview into a (static or dynamic) model on the other hand. Three issues have been identified as very important for this translation:

- the choice of the balancing items
- the choice of the fixed variables
- the derivation of the distribution coefficients.

In Section 9.2, these conclusions regarding the *quantification* step drawn from the case studies are presented.

A second aspect concerns the case studies themselves, as presented in Chapters 7 and 8. In Appendices 2 (cadmium) and 3 (nitrogen), a sensitivity analysis has been performed. In Section 9.3, the results of this sensitivity analysis are summarized. The main question here is: what, in retrospect, is the reliability of the outcome of the case studies? The evaluation has been made with respect to:

- the data used in the bookkeeping system, their margins of error and the consequences of that for the statements that can be based on the quantified overview
- the above mentioned translation of the bookkeeping overview into the model as made in the case studies
- the consequences of bookkeeping errors for the modelling outcome and the conclusions that have been drawn from that.

In Section 9.4, finally, a first attempt is made to define a general setup for a sensitivity analysis for SFA studies, based on the conclusions of 9.2 and 9.3.

9.2 Reflections on the quantification of the overview of flows and stocks

9.2.1 Setting up a bookkeeping system

A bookkeeping system consists of statistical and monitoring data. The most important issues, therefore, are the availability and quality of the data.

A very important source for the economic flows of many substances is trade and production statistics, which deliver data regarding the amounts of raw materials and products being imported, exported, and produced. The main uncertainty concerns the accuracy with which companies fulfill their obligation to provide the statistics offices with their data. The level of this uncertainty is unknown, but most probably minor since no important balance deficiencies occur. The Netherlands' Central Bureau of Statistics estimates a level of uncertainty well within 5% (Olsthoorn, oral communication). For case studies on the EU level, these statistics will continue to he useful in the future. For case studies at the country level within the EU, they will not. Since 1992, no more physical trade data are collected for EU countries. Translations must now be made from monetary data, with, inevitably, a severe concurrent quality loss. This is a major setback for

SFA and other material flow studies in general.

Data availability and quality regarding the content of substances in products and materials varies greatly. For some substances, such as a group of well-investigated heavy metals and nutrients, data availability is relatively good, and sometimes there even is the opportunity to compare data from different sources. For others, almost nothing is available.
Process data, from which distribution factors for the economic flows can be derived, are available in patches. In most cases, this is a problem of confidentiality rather than lack of knowledge, since many of those processes are related to production in individual companies.

Data regarding economic stocks, i.e. products and materials locked up in the *use* stage of the life cycle (in households, buildings, waterpipe and sewer systems, etc.), are hardly ever available. This is an important information gap for substances used in durable applications, especially for predictions of future situations, since these stocks determine the future waste streams to a large extent. Investigations in this direction have been started in some countries, but not as yet in the Netherlands. Not only is the present size of the stocks important, but equally important are the life span of the applications, the extent of market saturation and the sensitivity for fashion — in short the stock dynamics. The lack of information regarding the stock dynamics implies that not just the SFA predictions, but *any* predictions concerning waste streams in the future must be regarded with great caution.

Availability and quality of solid waste stream related data is also variable. A general source is the OECD environmental data. The margins of error for these data are unknown, but probably considerable, since these statistics are usually incomplete or based on much older measurements. Not only the amount, but especially the composition of municipal waste is rather uncertain. A margin of 50% up or down could easily be reckoned with.
Emissions and emission factors are generally available for the situation in the Netherlands, due to the Emission Registration (ER) on the one hand and the SPIN-investigation on the other hand. The ER data, in particular, may be of doubtful quality, since these questionnaire-based data are hardly ever checked. Extrapolation of these data to other countries is sometimes necessary, but often suspect.

There is an enormous body of data regarding environmental flows. Some of these can be used directly, such as the transboundary river loads. Most of these, however, cannot be applied directly, because they refer to very specific local situations. Rather rough assumptions must be made with regard to the environmental flows for which the data may only serve as a general check. Often, even this is not possible, since local circumstances influence environmental flows enormously. Depending on circumstances, for example, the leaching of nitrates to the groundwater may vary from nothing to more than half the soil load. It is difficult to imagine how to overcome this lack of general or average data. Using a general multimedia model of the environment instead of data could provide a way out in some cases.

The collected data on flows and stocks must be organized into a comprehensive overview. Bringing together data with widely varying but sometimes considerable margins of error can limit the possibilities for basing statements on the overview of flows and stocks. The act of combining data into an overview, however, also increases those possibilities: attempting to establish a complete and coherent overview in itself acts as a powerful check. This may appear in different ways:

1. If a node appears to be completely out of balance, one is induced to look into the figures in more detail in order to spot the problem, which may be a missing flow or a data error.
2. Some flows can be more accurately estimated indirectly, as a balancing item, rather than

directly, based on measurements. This is especially true for accumulations (which, in fact, are not flows but stock modifications). Also, doubtful data, such as for example waste generation data can be checked in this way, as has been done for example for the "remaining waste" in the case of cadmium.

3. **A node's input as well as output generally consists of a number of separate flows. On the level of the total input and output, respectively, relatively large inaccuracies in one specific flow may become less important. This is even more true in the case of summarized flows on the level of the system as a whole, such as the emissions total or the total environmental accumulation.**

9.2.2 Translating the bookkeeping system into a model

In Appendix 1, some calculations have been made with regard to two example systems: the system EXAMPLE that has also been used in Chapter 3 when explaining the SFA modelling techniques, and the system SIMPLE, with 10 nodes and 25 flows, which represents theoretical flows of nitrogen in a theoretical area. When translating a bookkeeping system into a linear model, there are various possibilities to do so. It is possible to obtain an overview of flows and stocks that is identical to the bookkeeping overview with different models, obtained by a number of routes. The differences only appear when the model is used for calculating purposes, for example establishing the effects of a regime change. Basic steps that must be made in the translation procedure are:

- the choice of the fixed variables
- the choice of the balancing items
- the derivation of the distribution coefficients.

Several possibilities have been tested to determine their consequences for the outcome of model calculations. Various setups of the model of SIMPLE have been subjected to a marginal analysis, in order to establish the sensitivity of the modelling parameters for changes (and, at the same time, for margins of error). With EXAMPLE, the impacts of different modelling setups on the steady state situation belonging to the unchanged regime have been tested as well. Below, the results of these operations, as they are presented in Appendix 1, are summarized.

The choice of the fixed variables

The influence of the choice for the fixed variables was tested in both EXAMPLE and SIMPLE. In EXAMPLE, three possibilities were calculated: fixed inflows, a fixed internal flow, and a fixed internal stock. In SIMPLE, fixed inflows were compared with a fixed demand for N in food. This issue appears to be of crucial importance. In both EXAMPLE and SIMPLE, regime changes (or, therefore, data errors) resulted in completely different reactions when different variables were appointed as the fixed ones. Not only differences in the absolute figures were found, but also differences in the direction of the changes. A regime change would lead to an altogether lower level of flows and stocks in one case, but a higher level in the other. It would appear that this is Perhaps the most critical issue when translating a bookkeeping overview into a model. Again, it is advisable to choose the fixed variables as much as possible according to causality in the real world. This is all the more difficult, since different types of causality exist: physical and economic causality. The physical causality is the most important type if an origins analysis is performed. The chain of physical causality starts at the cradle and ends at the grave. Therefore, the system's inflows are indicated as best candidates for the fixed variables. When calculating the impacts of regime changes, economic causality is more important. Economic causality is the causality of supply and demand, the driving force behind the economic substance flows, the reason why the substance chains from-cradle-to-grave are there to begin with. An inelastic supply would point in the direction of the system's sources as fixed variables, an inelastic demand in the direction of the use flows or use stocks. This will not always be an easy choice to make, since it is not always

overwhelmingly clear on which side the major inelasticities can be found. Moreover, it depends on the scale level of the analysis: a small region has other "laws" than a country or a group of countries. It also means that in many cases the model used for the origins analysis, which by necessity has the system's sources as the fixed inflows, is not suitable for evaluating regime changes.

The choice of the balancing items

It appears that the balancing items are responsible for an important part of the system's sensitivity for changes. The similarities between the marginal analyses of the bookkeeping system and of the model illustrate this. Since every node has a balancing item in SFINX, a rather large part of the equations consists of balancing equations, both in the bookkeeping option and in the modelling option (10 out of 25 in SIMPLE). This also implies that the difference in reaction between a bookkeeping system and a model can be less pronounced than would be expected. This is sustained by the results of the sensitivity analysis for the cadmium case study in Appendix 2. This implies that the choice of these balancing items must be made carefully, and as much as possible in line with what variables are actually the balancing items of the process, i.e. variables that have no independent role in determining the processes in- and outputs. In a case of physical causality, therefore, the node's accumulation or stock change would apply as the best candidate. When the system is demand-driven, the supply flows may best serve as balancing items, since their magnitudes are determined by the demand.

Derivation of distribution coefficients

The distribution coefficients, although they are the principle characteristics of the processes involved, appear to be less important than one would imagine beforehand. In calculating the steady state situation, different ways of expressing a node's outflow as a function of the inflows do not result in different overviews in the EXAMPLE system, as can be seen when comparing the three different models based on EXAMPLE, TEXIMPL1, 2 and 3, in Appendix 1. The reaction of the three different files to regime changes is also very similar. It would appear that the starting situation, the bookkeeping overview, does not leave room for great differences in this respect. It also supports the conclusion drawn in Chapter 3 and again in Chapter 4, that the steady state offers the best basis for regime comparisons, since many uncertainties, especially regarding the stocks, are excluded. When setting up a dynamic model, or when using a static model to calculate the effects of regime changes in the manner of the National Environmental Outlook (i.e., without applying this to the steady state situation, just as has been done in the cadmium case study) this may be different again. In such cases, especially, the exclusion of stocks may lead to a less than adequate modelling result.

93 Evaluation of the conducted case studies on cadmium and nitrogen

The first step in both case studies has been to set up a bookkeeping system for a year in the recent past (1987 for cadmium, 1988 for nitrogen). The data used for that step originate from many sources. Below, and more extensively in Appendices 2 and 3, these data are evaluated with regard to their reliability and the influence of possible errors on the resulting overview of flows and stocks. The second step, then, is the translation of the bookkeeping system into a model used to perform the origins analysis on the one hand, and to obtain an impression of the impacts of certain pollution abatement measures on the other. In Section 9.3.3, some general conclusions are drawn regarding the case studies and the robustness of the statements that have been made in Chapters 7 and 8.

9.3.1 The bookkeeping overviews of cadmium and nitrogen

The overview of flows and stocks is built on data from different sources. Trade, production and environmental statistics are important sources in all cases. Apart from that, specific studies regarding substances in the environment, emission registrations and inventories, waste stream related studies, and data regarding the composition of products and materials have been used. In Appendices 2 and 3, each of the flows out of the bookkeeping overviews of the case studies is discussed with regard to its source(s), the assumptions that have been made, and the known or expected margins of error. In this section, the main conclusions of the evaluation are presented. The specific details can be viewed in Appendix 2 (cadmium) and Appendix 3 (nitrogen).

The bookkeeping overviews contain not only more or less reliable data, but also rough guesses and flows estimated as balancing items of a certain node. In general, there is a difference between data regarding economic flows/stocks and environmental flows/stocks. On the economic side, the trade and production statistics are an important and rather reliable source. No such source exists for the environmental flows, but there are many detailed investigations from which data are available. Both cadmium and nitrogen have been intensively investigated.
Below, the selection of variables that have been varied in a sensitivity analysis is presented. The sensitivity analysis has been performed in order to evaluate the robustness of the outcome and the statements that can be based on that. Two criteria for selection have been used:

1. The most important criterion for selecting variables to vary in a sensitivity analysis is their being unknown or highly inaccurate, based on rough assumptions or estimated as a balancing item.
2. Another criterion is the expected impact of changes in one variable on others. In a bookkeeping system, this last criterion is of limited importance, since most of the variables are independent from others. Trade-off occurs mostly through the balancing items.

The sensitivity analysis is performed with specific attention for the influence of errors or modifications on the emissions and environmental flows. For these flows, accurate and detailed standards and policy targets may exist, and it therefore is important to have an insight into their accuracy.

The cadmium bookkeeping overview

In comparison to the rather reliable trade and production statistics uncertainty increases for the Cd-content, for which data are generally less reliable. This is due partly to large differences in cadmium concentrations in both raw materials and specific products (especially so if Cd occurs as an unintentional contaminant), and partly to the fact that Cd occurs in very low concentrations in most applications. In general, the higher the concentration, the more reliable the data are. Data regarding the Cd content in waste streams are scarce and based on very crude estimates. From the various sources, at least a factor 2 uncertainty margin appears.

For the environmental flows, emission factors and distribution coefficients have been used in most cases. The emission factors can be regarded as relatively well investigated in the case of cadmium. The uncertainties in the environmental flows, especially runoff and leaching, are very large because measurements always refer to very specific environmental situations. In this case, a margin of an order of magnitude either up or down would not be impossible. However, for some substances, and for cadmium as well, there have been extensive studies regarding specific flows such as sewage sludge and fly ash, which can be used to narrow down the margins of error.

In order to obtain insight into the consequences for the overview of stocks and flows, a sensitivity analysis has been performed for a number of data, based on the above mentioned two criteria

(being unknown, or probably influencing other flows):

- the amount of cadmium in municipal and other waste streams (doubled and halved)
- the emissions of cadmium into the atmosphere (doubled and halved)
- a different interpretation for the industrial waste water treatment data
- **the amount of cadmium in iron and steel (a factor of 10 higher)**
- **the amount of cadmium in phosphate rock and derived products (doubled and halved), combined in different combinations with the cadmium content in agricultural products (also doubled and halved)**
- the processes of runoff (factor of 5 up and 10 down) and leaching (factor of 10 down), which are estimated by distribution factors since no data on these flows exist for the European Union level.

A detailed argumentation and description can be found in Appendix 2.

In the case of cadmium, almost invariably the unknown flows of either landfill or economic accumulation were chosen as balancing items. Any of the variations that have been introduced therefore automatically are shifted to landfill on the one hand and economic accumulation on the other. These large Cd sinks are therefore the most uncertain and vary the most from the assumptions. However, their sheer magnitudes serve as a mute for impacts: large changes in an absolute sense are relatively small for these two items.

As most influential, the Cd content in phosphate raw materials and products and the assumptions regarding the environmental processes of runoff and leaching have appeared. The Cd content in P directly influences the agricultural soil balance, the surface water balance, and with those two also the groundwater and sediment balances. The assumption regarding runoff, which is an assumed distribution factor and not a figure from literature, has a large influence on the surface water balance. The runoff from landfill sites could amount to a considerable quantity even if it is a small percentage, because of the magnitude of the amount of landfilled Cd. The same is true for the process of leaching to the groundwater.

The bookkeeping overview therefore appears to be rather robust against the influence of changes. In almost all cases, the environmental flows (except landfill) are hardly influenced by changes in the economic flows. Conclusions based on the bookkeeping overview, such as stated on p .. of Chapter 7, the cadmium case study, would appear to be still valid under different assumptions for certain variables, such as tried out in Appendix 2. The possible influence of bookkeeping errors on the cadmium model and the conclusions based on that, will be treated below in Section 9.3.

The nitrogen bookkeeping overview

The major part of the economic flows in the N bookkeeping system refers to agriculture. Two fo the main sources for this part were the Eurostat agricultural balance sheets, for the agricultural products, and the Veevoedertabel for the N-content in those products. N in agriculture is much better investigated than cadmium. Therefore, the resulting overview at least for the agricultural flows can be expected to be more reliable. Main uncertainties can be detected in the grass production on the one hand, and the manure production on the other hand. A sensitivity analysis performed for these two flows shows that these uncertainties mainly negate each other and hardly influence other flows.

For the environmental flows, the air balance has been investigated in great detail. Here, the EMEP balance for NO, and the RIVM balance for NH_x, primarily made up in the very intensive and detailed studies regarding the acidification problem, were available and have been used. For the other environmental flows, the assumptions fall in the same category as those for cadmium. Trying out other assumptions for the N-bookkeeping system shows that the shifts that occur have

shorter chains than for cadmium, and do not influence the looped process cycles as they did in the case for cadmium. In all, it appeared that the nitrogen bookkeeping overview is very resistant to changes, and even more robust than the cadmium overview.

9.3.2 The setup of the cadmium and nitrogen models

In this section, the sensitivity of the cadmium and nitrogen models, such as those used to perform the origins analysis and to calculate the effects of measure packages, is tested. The influence of the following choices is evaluated:
- margins of error in the fixed variables
- margins of error in the distribution coefficients
- the introduction of stocks as variables
- the use of the steady state situation as a basis for comparison.

When translating the bookkeeping system into the model, several explicit choices must be made. These refer to
- the choice for the balancing items
- the derivation of the distribution coefficients
- the choice for the system's fixed variables.

In Section 9.2, some general remarks have been made with regard to these issues. In this section, arguments are presented to explain the rationale for making these choices in the manner they have been made in both case studies, in the process of translating the bookkeeping overviews into models.

The cadmium case study model

In setting up the model in the cadmium case study, the choices made have been:
- balancing items — in almost all cases, accumulation or solid waste to be landfilled
- distribution coefficients — in almost all cases, a straightforward use of the bookkeeping overview, calculating the nodes' outputs as a fraction of the totalized input
- fixed variables — the system's sources.

Good arguments can be found to support these choices: the accumulations can be seen as the "real" balancing item of every node, the difference between IN and OUT. For the distribution coefficients, no arguments can readily be found to derive them in another fashion. Considering the system's sources as fixed variables seems to be the best choice in the case of cadmium, since the supply of cadmium is related almost entirely to the supply of zinc and phosphate and is therefore very inelastic. As a result, the consequences of making other choices have not been tested.

The steady state situation has not been used in the cadmium case study, and the stocks have not been included in the investigation. This last inclusion would not have been possible since virtually no data exist regarding these stocks. In Appendix 2, the influence of this on the results of the calculations has been tested. Two alternative cadmium models, wherein stocks have been included, have been defined. These models both refer to the steady state situation. The impacts of several regime changes (or data errors) were calculated to evaluate the robustness of the cadmium case study in this respect. Several of those changes are identical to the modifications tested in the bookkeeping system, so that there is also an opportunity to make a comparison between the reactions of the bookkeeping system to changes to that of the model:
- changes in the amount of cadmium in waste in 1987
- changes in the system's fixed inflows (zinc, phosphate, iron and cadmium)
- changes in the uptake of cadmium in agricultural products
- changes in the environmental processes of runoff and leaching
- the impacts of battery recycling.

In general, the changes that have been calculated in the model have impacts in the same direction as the bookkeeping system. Most changes have their largest impact on either economic accumulation or landfill. An obviously stronger effect can be detected with regard to changes in the system's sources, especially phosphate and zinc, but in the same direction as the changes in the bookkeeping system. The larger uptake by crop significantly magnifies the agricultural cycle, which does not appear in the bookkeeping system.

The model used in the case study and the two long term steady state models react rather similarly to the changes. The impacts are somewhat magnified in the steady state models, especially the impacts of changing the amount of Cd that flows into the system with zinc. The only difference in reaction can be found when calculating the impacts of introducing cadmium battery recycling. The largest change is in the same direction: a larger accumulation in the model used in the case study is mirrored by a larger stock in both steady state models. However, the impacts on the environmental flows are contradictory. The two steady state models show slightly smaller environmental flows, while the model used in the case study leads to slightly larger flows. The changes are very small in all three cases, however, so the conclusion could also be that the environmental flows are barely influenced by this measure.

The nitrogen case study model

In the nitrogen case study, the choices for setting up the model have been made as follows:

- fixed variables: the demand for N in food (i.e. proteins) and the application of industrial fertilizer within the EU have been the most important fixed variables as regards the calculation of the impacts of regime changes
- since no accumulation is incorporated in the model, different flows have been selected as balancing items. In the food production cycle, the balancing items have been derived from the demand: so much food requires so much production, requires so much fertilizer, etc. Downchain, different flows have been appointed as balancing items, in most cases waste flows or emissions.
- distribution coefficients: in the agricultural system, a difference has been made between the uptake efficiencies of the various fertilizers, based on literature. The distribution of N over the various crops and to the various destinations in the environment has been derived from the bookkeeping overview.

Here, too, the appropriateness of the choice of the fixed variables and the derivation of distribution coefficients can be supported by arguments. In the case of nitrogen, the demand for proteins by the EU population will be by far the most inelastic part of the economic life cycle. The fertilizer application has been appointed as a separate fixed variable in order to be able to calculate changes regarding the level of this flow; this would not be possible if the magnitude of it were derived from the required production level. It would seem useful to account for differences in animal manure and industrial fertilizer uptake efficiency, since many of the nitrogen related problems have to do with this difference.

Since the basic choices all are made with arguments and since the steady state situation has in fact been the basis for comparison in the case of nitrogen, the only items worth testing were the distribution coefficients. The crop/grass uptake efficiency coefficients have been selected as the most relevant ones to vary. It appeared, as can be viewed in Appendix 3, that the variation of the agricultural distribution coefficients did not influence the results of the calculations in such a way that different conclusions could have been drawn in Chapter 8.

The most profound, and at the same time the most debatable conclusion is the incompatibility of the current agricultural production with the absence of groundwater pollution with nitrates. To establish the robustness of this conclusion, another test has been performed. The required increase

of the uptake efficiency, needed to reach a 50% decrease of the flow of nitrates to the groundwater in combination with the 1988 agricultural production, has been calculated. It appeared that for all fertilizers, the industrial as well as the organic, an 80% uptake efficiency would be required. This seems a rather unrealistic percentage, although theoretically not entirely impossible, supposing major changes in technology occur. It seems likely that a breaking down of the EU agriculture in types of soil, types of crop and levels of application would provide additional information on where, how and to what extent a substantial increase of uptake efficiency may be achieved. This major task will not be undertaken within the framework of research for this thesis.

9.3.3 Conclusions regarding the cadmium and nitrogen case studies

When considering the case studies discussed in Chapters 7 and 8 in the light of the choices that have been made in the translation from a bookkeeping system to a model, one can conclude that the results of the nitrogen case study are more robust than those of the cadmium case study for three reasons:

1. The present deviation from a steady state situation is much larger in the case of cadmium, where roughly 70% of the inflow into the economic system accumulates. Cadmium is included in many different products with widely varying and, moreover, unknown life spans while nitrogen is confined for the most part to the agricultural system with a turnover of 1 year.
2. The steady state situation has been used to compare the different regimes in the nitrogen case study, but not in the case of cadmium. It has appeared from the EXAMPLE calculations once again that in the steady state, some uncertainties, especially with regard to the stocks' influence on the flows, are excluded.
3. The choice for fixed variables is more difficult to make for cadmium, although arguments can be and have been found. For nitrogen, the most sensible choice would obviously be, and has in fact been, the use flow or demand, since consumers* demand for food products in general and more specifically proteins is inelastic. In the case of cadmium, the inelasticity is on the supply side, because of its recovery as a byproduct of zinc. This would be an argument in support of the choice, such as it has been made in the case study, for the system's inflows as the fixed variables. On a smaller scale level - not the European Union, but for example, the Netherlands - where imports and exports are large compared to the primary production, this argument would not be valid. In such a case, it would perhaps be better if the use flows or even the required users stocks were appointed as the fixed variables. Even on the EU level, imports and exports of cadmium and cadmium products - although relatively small - somewhat obscure the picture.

When considering the evaluation of the bookkeeping overviews, once again nitrogen has the advantage:

1. The flows of agricultural products are very well investigated and presented in the Eurostat agricultural statistics with detailed balance sheets.
2. The content of nitrogen in the different agricultural products is also a much examined issue, from which detailed and usable data are available. The agricultural cycle determines the main part of the nitrogen overview. For cadmium, much more variation exists regarding the content in raw materials and products. Sometimes it has even been difficult to trace products in which cadmium appears, let alone in what amounts.
3. The environmental flows of nitrogen, the especially the atmospheric ones, are investigated in great detail in acidification research programs. With regard to processes such as leaching and runoff, the uncertainties are equally large for nitrogen and cadmium.

In all, one can reasonably conclude that the outcomes of the nitrogen case study are more accurate than those of the cadmium case study. Data availability and quality is better for nitrogen, the system is simpler, the modelling choices have been easier and more obvious. Also, time has played a role: the SFA methodology was further developed by the time the nitrogen case study started. Cadmium, therefore, has served a more important role in the earlier stages of SFA development as a methodological case study, by its complexity as well as its timing. The question of whether or not the statements made in Chapter 7 (which contains the cadmium case study) are still valid can, however, be answered affirmatively, as appears from Appendix 2. While the actual figures might have come out differently if other modelling options had been chosen, the conclusions themselves with regard to the origins of the cadmium related environmental problems and the usefulness of the proposed measures are not undermined.

9.4 A general procedure for a sensitivity analysis

In the above (and more detailed in Appendices 1, 2 and 3) a sensitivity analysis is one of the subjects discussed. In Appendix 1, a marginal analysis was performed for two example systems. In Appendices 2 and 3, a sensitivity analysis regarding various assumptions has been performed for the two case studies, the results of which are discussed in Section 9.3. In view of the many uncertainties connected with both the data and the translation of the bookkeeping system into a model, it would be an important step to arrive at some sort of a standard setup for a sensitivity analysis for SFA case studies, which left room at the same time for the role played by the specific details of the case study.

When conducting an SFA case study, data from many sources are brought together. At present, validation is only possible for a selection at most, but not for the whole set of data. For a very few parameters at most, series of measurements exist which could be used to comment on the accuracy and the margins therein. Therefore it is difficult even to estimate what the margins of error are. What remains as a possibility is a sensitivity analysis: varying parameters in order to evaluate the robustness of the outcome in light of possible data errors.
In view of the many uncertainties of different types, a sensitivity analysis can be recommended as a standard addition to every case study. Such a sensitivity analysis may best be set up according to a more or less standardized procedure. On the other hand, there must be room for the specific details of the case study to play an important role. From the above, it has become apparent that a difference must be made between bookkeeping systems on the one hand and models on the other, since the influence of possible data errors or inaccuracies on the results works through different mechanisms. It has also become apparent that the reconstruction of a situation in a past year is different from using a model to estimate the impacts of regime changes. Partly, the two differences coincide, since a bookkeeping system is always made up for a past year. However, models are not only used for calculating regime changes, but also for evaluating such a past year, as is the case, for example, when conducting an origins analysis. To some extent, moreover, the system's reaction to data errors corresponds with its reaction to regime changes. However, there are a number of aspects that do not show in a representation of the past that are important for an evaluation of regime changes. Therefore, this will be treated separately below.

The key question in every case is, how to cause a selection of parameters to vary. A number of criteria can be applied for this:

1. parameters of known inaccuracy (e.g. missing data, balancing items, non-fitting balances, contradictory data)
2. parameters of known or suspected "sensitivity", i.e. small changes having big consequences

3. parameters of known "importance", i.e. required to deliver results with a small margin of error.

Ad 1. Unknown or inaccurate parameters in a bookkeeping system refer to flow data. In a model, both flow data (the fixed variables) and process data (distribution coefficients) may be unknown. However, distribution coefficients, if unknown, can be derived from a bookkeeping overview. This means that uncertainties in bookkeeping data must be regarded from two angles: (1) the angle of their influence on the bookkeeping overview, and (2) the angle of their being used to derive distribution coefficients. This last issue will be a problem especially for processes with a time delay, such as entry into the waste stage of economic stocks.

Ad 2. Parameters of known sensitivity will be found among modelling parameters more than bookkeeping data. In a bookkeeping system, the influence of errors in one flow on others is necessarily limited, since for every separate flow data are collected separately. The only way errors can filter through the system is through balancing items. In a model, on the other hand, all flows depend on other flows or stocks, and errors in distribution coefficients are bound to influence many flows. Performing a marginal analysis is recommended as a standard procedure to identify sensitive parameters. Especially in cases of cyclic processes, such as recycling of waste materials and the agricultural flows, there may be self enforcing mechanisms which can cause relatively small errors to have large impacts. In cases of small flows derived from large ones, errors in distribution coefficients can be expected to have a large influence as well - the difference between 100 and 99 is 1%, but the difference between 1 and 2 is 100%! In a model, the fixed variables determine the magnitude of the other flows. Errors in the fixed variables may therefore be expected to have a larger effect than in the case of a bookkeeping system.

Ad 3. Important parameters will be linked mostly to the emissions and environmental flows, since for these flows accurate and detailed standards and policy targets may exist by which they must be evaluated. While with some bulk flows such as landfilled waste or economic accumulation a margin of error of 50% is acceptable, this may not be the case for atmospheric deposition, for example.

9.4.1 Evaluation of the overview of a year in the past

Bookkeeping system

The procedure for the evaluation of a bookkeeping system as to its sensitivity to inaccuracies in the basic data could be as follows:

1. Selection of data to vary
   - unknown flows: missing data or obvious wild guesses; for these flows, large margins of error may be tested for their effects on the overview
   - flows of known inaccuracy: in the case of contradictory sources, the effects of making another choice for the source that is to be "believed" can be calculated; in the case of an unreliable source, large margins of error either up or down may be tested
   - flows that must be known quite accurately: for these flows, data unreliability can be tested as well. It is more important, however, to select these flows as a basis for the evaluation, in other words to establish the effects of changes in other flows on these important flows. The important flows in this sense are the flows connected directly to the environmental (pollution) problems.
2. Determining the margin of error that will be introduced. This depends very much on the source in question. For some sources, a 5% margin is adequate, while for others an order of magnitude is indicated. The average quality of the source, the data being supported by

other sources, and the outside limits regarding the balance of the node all are important for deciding what the margins should be. Generally, it is advisable not to make them too narrow.

3. Testing each of the selected changes separately: making the changes as defined in the set of equations, and establishing the influence on the selected important flows.
4. Testing combinations of changes: one may suspect, or it may appear from the tests, that some of the changes work in the same direction, and in combination may reinforce each other's impacts. These changes can be tested out in combination.
5. Evaluation of the robustness of the outcome: establish whether the conclusions drawn from the overview of flows and stocks can be undermined by faulty or inaccurate data, or by making other assumptions when combining the different sources.

Static model

1. Selection of data to vary. This can apply either to fixed variables or to the distribution coefficients. The sensitivity of both can be tested in a marginal analysis. For the fixed variables, the same procedure can be followed as in the case of a bookkeeping system. Distribution coefficients may come either from process data (e.g., emission factors of industrial processes), or they may be derived from the bookkeeping overview. In almost all cases process data refer to technical coefficients. The distribution over the various economic outputs of a process, which is not physically but economically determined, must always come from bookkeeping data. While for technical coefficients a margin of error can often be assigned, either from literature sources or from estimates of individual companies, this is much more difficult for economic coefficients. These data, although they exist, are hardly ever available for reasons of confidentiality. They almost invariably must be constructed by combining production and trade statistics.
2. Determining the margin of error that will be introduced. In the case of fixed variables, see above under *bookkeeping system.* For distribution coefficients, these margins may be drawn from different sources within the literature, in the case of conflicting sources. This will only occur for the technical coefficients related to specific processes. The limits to the margins of error may also be determined by the node's balance. Often, there is not much space for variation because the nodes may be out of balance (negative flows, obviously wrong accumulations, leading to impossibilities in upchain or downchain nodes). In this way, the construction of the overview of flows and stocks acts as a powerful check on itself.
3. Testing each of the selected changes separately and establishing their separate influences on the selected important flows.
4. Testing combinations of changes. Here, more than in the bookkeeping system, changes will cause reactions throughout the system that may reinforce one another. Combinations can best be made after testing the separate changes.
5. Evaluation of the robustness of the outcome: establish whether the outcome will change in such a manner that the conclusions drawn in the case study are undermined.

9.4.2 Evaluating regime changes

Evaluating regime changes can only be achieved with a substance flow model, either static or dynamic. The experience of the case studies, and therefore also the recommendations of this section, are limited to the use of static models.

From the above, it has become apparent that a number of basic issues are very important for the modelling outcome:

- the use of the steady state situation

- the choice of the fixed variables
- the choice of the balancing items
- the derivation of the distribution coefficients.

The last issue is discussed above. For the other three, it is important that the choices are made carefully and with good arguments. If this is difficult - for example, if there is no obvious candidate for a balancing item, or there is no question of an obviously supply or demand driven system - then it may be advisable to try out different options and assess the reaction of the various alternative systems to regime changes, as has been done above for the small systems EXAMPLE and SIMPLE in Appendix 1. If, in the case of static modelling, the steady state situation is not used (there may be reasons for making such a decision) then at least it should be established whether or not this would have led to results that point in another direction. Here, again, a marginal analysis may provide relevant information, since the sensitivity for errors of flows and stocks in either the fixed variables or the distribution coefficients equals the sensitivity for regime changes.

An additional issue refers to the determination of the robustness of the static model, if it is used for comparing different regimes. The question then must be reversed: instead of asking whether under certain assumptions a certain conclusion is still valid, the question must be posed under which model conditions the conclusion could *not* be drawn in the same manner. If that point of reversion still is characterized by a likely - or at least a physically and logically possible - set of equations, then a more careful investigation or a more thorough data check is required. This approach has been taken in the nitrogen case study, as described above and in Appendix 3.

It is possible that, since the demand on the accuracy of a sensitivity analysis is generally higher, there may be additional requirements for dynamic models. That has not been worked out further.

PART V DISCUSSION, CONCLUSIONS, RECOMMENDATIONS

In Pan V, the main findings of the study are discussed. This final Part contains only one chapter, Chapter 10. In this chapter, the contribution of this thesis to SFA methodology development, and the potential of SFA as a policy supporting tool are evaluated, and some recommendations for further research and use are made.

The general framework, as described in Part II of this thesis, may well serve as a general framework for all SFA applications. Thereby it can act as a means to bring more coherence in the SFA scientific field, which is at present very scattered. The details of the framework as they are worked out in this thesis are unfinished and in some places still very sketchy and disputable, but the main items of the system's definition in time, space, substance and function, the quantification by bookkeeping, static modelling or dynamic modelling, and the interpretation by a coherent set of indicators, bring the SFA methodology a step further.

SFA can play a role in environmental substance policy in analyzing the connection of the economy with the environment in a physical sense. By doing so, it becomes possible to link environmental problems to their origins, and to estimate the effectiveness of certain abatement measures as well as the occurrence of problem shißing connected with these measures. The use of SFA is particularly required in cases of substances with a relatively complicated economic life-cycle and/or application in durable products. The applications state, origins and solutions are sufficiently worked out for practical application in support of environmental substance policy. Both footprint and predictions require further methodological development.

CHAPTER 10 DISCUSSION, CONCLUSIONS, RECOMMENDATIONS

10.1 Introduction

In this chapter, the main findings of the study are discussed. On the one hand, certain conclusions can clearly be drawn. On the other hand, many discussions are still open, and the research territory has by no means been fully explored. Further development of SFA may increase its potentials as a policy supporting tool. The evaluation is conducted in terms of the two perspectives of this thesis: (1) SFA methodology development and (2) the role of SFA supporting environmental policy.

SFA aims to provide the relevant information for a region's overall management strategy with regard to one specific pollutant or a limited group of pollutants. In order to do this, a quantified relationship between the economy and the environment of a geographically demarcated system is established by quantifying the pathways of a substance or group of substances in, out and through that system. This general definition leaves ample space for many specific applications of the SFA method in response to the specific questions that arise while formulating a substance policy. An analogous general framework for all SFA studies is presented in Chapter 2, but the more detailed decisions that must be made within this framework depend on the specific application, as has been worked out in Chapter 5.

In Section 10.2, the methodological aspects of SFA are discussed: the position of SFA in the field of integrated chain analysis, the general framework, and the methodological choices within the framework. In 10.3, the present and potential role of SFA in environmental policy is discussed. In Section 10.4, the overall conclusions of this thesis are stated. These are conclusions regarding the position of SFA in the field of integrated chain analysis, the SFA methodology, the conducted case studies, and the value of SFA for environmental policy. In Section 10.5, several recommendations for future research and use of the SFA tool are formulated. Section 10.6, finally, contains some concluding remarks.

10.2 Substance Flow Analysis: the methodology

10.2.1 The position of SFA in the field of integrated chain analysis

SFA has been developed as an analytic tool to support an integrated substance chain management. As such, it has its possibilities but also its limitations. It is important to have a clear understanding of these limitations. No demands must be made of it that transgress these, which are centered around two aspects:

1. The SFA point of view considers the world in terms of substance flows and stocks. Therefore, no outcome can be expected in other terms than those. Aspects of space occupation, physical interventions and the impacts on the natural environment are not included. The same can be said of societal issues such as costs, behaviour and values. These aspects may serve as a background for an SFA study - for example, as policy targets for emission reduction, or hidden in the distribution coefficients of a substance flow model - but the actual SFA outcome is not in these terms.
2. The SFA instrument only takes one substance or a limited group of substances into account at a time. While various mechanisms of problem shifting - within the substance chain, to the future, to other areas - can be analyzed, the problem shifting to other substance chains cannot. For this,

other tools of integrated chain management, such as LCA or MFA, are more appropriate.

Secondly, there is the question of standardizing the SFA tool. So far, there has been little attention for harmonization of the efforts in this field. Steps towards harmonization require an agreement on two levels:

1. The proper place of SFA in the field of integrated chain analysis, and the relation of SFA with the other analyzing tools, as mentioned above. In Chapter 1 it has already been stated that these tools have much in common. The development of the different methodologies therefore could benefit greatly if conducted in harmony, not only by spotting the differences but also by adopting similar procedures and even identical steps regarding system's definition and modelling, if proper to do so.
2. The SFA tool itself. It would be an important step forward if the scientific field could agree on a general framework such as presented in Chapter 2. However, as shown in Chapter 5, it appears that each specific SFA application has its own specific requirements regarding the specifics of the system's definition, the appropriate type of modelling and the most suitable form of interpretation of the results. Discussions regarding harmonization and standardization of SFA must be conducted while keeping this in mind.

10.2.2 The SFA framework

The SFA framework stated in Chapter 2 is presented as a procedure for materials and substance flow studies in general. This general framework can serve as the starting point for a general discussion to determine which methodological choices consequently have to be made, how those choices might be affected by the aim of the study to be conducted, and what the implications are for the conclusions policy makers may reach. The framework consists of three steps:

1. definition of the system
2. quantification of the overview of stocks and flows
3. interpretation of the results.

System's definition

As is argued in Chapter 2, the system's definition has to do primarily with the specification of the four basic variables: space, time, substance, and functions. The SFA system as described here is determined with regard to space (a region of any size from global to local), time (one year) and substance (one substance or a coherent group of substances), but integrates over all functions. A further specification can be made by the identification of subsystems, the categorization of flows and stocks, and the identification of processes to include within the system. The system represents the substance chain from cradle to grave. Two approaches can be followed to define this integrated substance chain: the *regional* approach, defining the system by its geographic boundaries, and the *functional* approach, taking the region's use or consumption of the substance as the starting point and specifying the cradle as well as the grave of this substance use, wherever it may take place. The regional approach therefore enables one to comment on pollution as it occurs in the region, the functional approach specifies the amount of pollution on behalf of the region. Both approaches may be useful.

These two approaches differ fundamentally and therefore lead to substantially different system definitions. Discussions regarding other, less influential issues, such as whether or not to define the lithosphère as a third subsystem, or the exact demarcation between economy and environment, have not been definitively concluded. Ft is imperative to define the system carefully with regard to these aspects for every SFA case study, with an argumentation derived from the demands of the specific SFA application involved, in order to be able to reproduce and interpret the results. However, it is not required to agree on a general system's definition that is rigidly determined

with regard to every detail. It may even be considered undesirable to do so, because of the loss of flexibility this involves.

Quantification of the overview

The quantification of the system's substance flows and stocks can be attempted in different ways. Three are identified in Chapter 3:

- bookkeeping: keeping track of flows and stocks by registering them afterwards;
- static modelling: specifying the relations between stocks and flows rather than the flows themselves, and calculating the overview of flows and stocks supposing a stationary state;
- dynamic modelling: including time as a modelling parameter, thereby making it possible to anticipate developments through time.

In discussions among scientists in this field, there is often a feeling that the dynamic type of modelling is more valuable than the others ("mere bookkeeping"). This may arise from the conviction that the *prediction* type of questions are the most important ones to answer. On the other hand, it may also be a consequence of a lack of insight into the other possible SFA applications. From the work on this thesis, it can be concluded that there is no "best" type of modelling. In Chapter 3 as well as in Chapter 5, it is concluded that all three have their own Policy supporting qualities. Bookkeeping is useful for monitoring the state of flows and stocks and the developments through time. Static modelling can be used for the analysis of the origins of Pollution problems and for comparing different abatement options. Dynamic modelling is useful for forecasting and scenario analysis.

In general, one of the most important issues for quantification by bookkeeping is the availability and quality of data. Both vary with the substance; some substances are intensively investigated, others hardly at all; for some substances, data confidentiality is a problem while for others not at all; some substances are more difficult to measure than others. Data regarding stocks, both in the economy and in the environment, are scarce or completely lacking for some substances. This is a Problem especially when the bookkeeping overview is used as a modelling input. In the conducted case studies and especially in the sensitivity analyses of Appendices 2 and 3, it appears that there was a difference in quality between cadmium and nitrogen data. However this does not influence the results in such a way that the conclusions based on the overview in Chapter 7 are undermined. As shown in Chapter 9, the act of combining the data in one overview also serves as a check and as a mute for data errors.

The use of the long term steady state situation as a basis for comparison is by no means a new idea. In economic modelling, this has been practised with success for decades, as is stated in Chapter 3. However, if this type of modelling is also applied on substance flows, it is regarded with suspicion by many environmental scientists, and as inferior to the dynamic type of modelling. Yet this comparative static modelling, if applied in its proper place, has distinct advantages over dynamic modelling. In the first place, the steady state modelling result is rather more robust, since (as proven in Chapters 3 and 9) the influence of the stocks is partly eliminated in the steady state situation. Secondly, mechanisms of problem shifting to the future are eliminated in the steady state situation, while they may, in the case of the dynamic model's predictions, remain undetected. Finally, the data requirement for dynamic modelling is more extensive. However, while the use of steady state modelling is eminently possible for comparing regimes and deciding which measures are effective and which are not, as was done in the nitrogen case study in Chapter 8, it must not be used to predict either the near or the distant future.

For predictions, priority should be given to the dynamic modelling. A major setback for this SFA application is that general dynamic substance flow models, although highly praised, are not available at present. In Chapter 3 some examples of dynamic models for limited systems are mentioned, as well as some plans for developing them on a more general level. Moreover, a

procedure is described to set up such a dynamic model.

A further discussion regarding dynamic SFA modelling refers to the value of predictions. It is virtually impossible to really predict the future, and any attempt to do so *on a detailed level,* which is the required level for this SFA application, is bound to be proven false. It « possible, however, to get insight into what the environmental situation would be if society were to develop along certain lines. This, then, is not a predicted future but a *potential* future from which the actual future situation will, more or less, differ. Comparing a set of potential futures can indeed be useful for environmental policy. It not only provides an insight in the potential of specific pollution policies, but also offers insight into the influence of basic societal changes on the substance flows without a specific policy directed at them. It is in that case an advantage, when the potential futures considered are not too narrowly defined along the lines of the current situation and developments.

On the other hand, we may ask ourselves what the added value of creating a picture of such potential futures is beyond the comparative static SFA application discussed above. The advantage of being able to compare policy targets with a potential situation for a specific future year may well fall away against the difficulties that must be overcome in order to make the modelling outcome sufficiently reliable to permit such a comparison. For really wild scenarios, such as have been introduced for example in Chapter 8 (the nitrogen case study), the steady state approach might even be preferred. It is easier to communicate that the outcome is not a prediction but rather an impression, and also to refrain oneself from indulging in false presumptions of accuracy.

However, drawing pictures of potential futures is an accepted and much valued part of environmental policy, which will not be altered by questioning the usefulness of the exercise. If this is taken as the starting point, then it should be done as well as it possibly can be done. In the case of substance policy, this implies application, and therefore development, of dynamic substance flow modelling.

Interpretation of the results

In Chapter 4, two types of interpretation of the SFA results (the quantified overview of flows and stocks) are treated:

- evaluation of the flows and/or stocks with the help of additional information regarding the harmful nature of the substance: policy targets, no-effect levels, equivalency factors or similar information
- translating the overview into a set of indicators for integrated substance chain management.

The first type of evaluation is by necessity limited to the environmental flows of the system. The second one enables one to use the information on the economic flows as well, thus providing opportunities to rise above the here-and-now and to comment on the various problem shifting mechanisms that can be detected: within the substance chain, to the future, and to other regions.

Much work has been done on the development of indicators for following the state of the environment and the performance of environmental policy. Long lists of such indicators are available, and various attempts to organize and classify them have been undertaken. Among these indicators are indicators for integrated chain management. In Chapter 1, different types of chains have been distinguished: product chains, materials chains and substance chains. In the development of indicators so far, the distinction between these three types of chains has not been clearly made, resulting in overlapping, omissions and unclear possibilities of use. In Chapter 4, an attempt has been made to define such a set of indicators for the substance chain. If the integrated substance chain management is accepted as a separate and important part of environmental policy, the development of such a set is almost a matter of course. It would be useful to develop a separate set for each type of chain, with an eye to the specific characteristics of each. The set

identified in Chapter 4 also needs further testing on various aspects, especially its completeness, the relevance of the separate indicators within the set, and the applicability in practice.

10.3 Substance Flow Analysis: its role in supporting environmental policy

10.3.1 The case studies

The proof of the pudding is in the eating, and the proof of developed analytic instruments is in the application. What has the application of SFA added to what we already knew in the case studies? In retrospect, three SFA applications have been practised in both case studies:

- an evaluation of the *state* of the flows and stocks for a year in the recent past
- an assessment of the *origins* of specific pollution problems
- an evaluation of different types of *solutions*, arising as a result of environmental policy or other factors.

The results of these applications have been used to outline a general management strategy for cadmium and nitrogen.

Cadmium

In the case of cadmium, the first result was the overview of flows and stocks for the year 1987. The advantage here is that by combining already existing knowledge, the individual data on cadmium flows are put in perspective. From this overview, the conclusion could be drawn, for example, that almost 70% of the inflow accumulated in the economy. This stockbuilding indicates a risk for a future increase in emissions.

A second result was an insight into the origins of several specific problem flows. The three levels of origins add useful information by organizing and avoiding double-counts or omissions.

The third result has been the insight into the futility of separate, in themselves useful, abatement measures in the case of cadmium. Because of the inelasticity of the cadmium supply, all measures result in problem shifting of one type or another. This has resulted in a management outline for cadmium wherein most of the proposed measures are incorporated, but with additional measures on crucial points: attention for zinc and phosphate as the main cadmium carriers, and the immobilization route - currently not applicable - as the only final way to prevent emissions.

Nitrogen

The added value in the case of nitrogen is, in the first place, the putting of all the different N-related problems in one framework. Thus, common origins have been detected for the various Problems on the EU level. The overview of the flows for 1988 has confirmed the statements regarding the extremely low efficiency of agricultural processes, especially those related to animal Production. In the scanning of potential solutions, two conclusions reached that were contrary to what some believed were that the current N-problems are not related to overproduction, nor are they related to the import of animal feed from outside the EU. It also appeared that the economy-environment confrontation related to feeding the EU population is a very serious one. Solving the N problems to the degree stated in various agreements cannot be attained by technical means only. It would imply abolishing agriculture-as-we-know-it, either by cutting down production to a tenth of its current level and importing the bulk of the food, or by shifting consumption patterns away from products of animal origin significantly. Here, SFA has contributed to making the incompatibility of feeding the current EU population with the absence of environmental problems apparent. The only alternative to suchlike revolutionary developments is setting the targets for environmental policy on a less strict level.

SFA thus has contributed especially in the area of making a quantified connection between economy and environment. This has led to some new conclusions on a detailed level. The main contribution however has been on the totalized level, by making apparent the various mechanisms of problem shifting that go hand in hand with several types of solutions.

10.3.2 The specific SFA applications

State: the evaluation of the present situation in a region
This type of SFA application is the only one with a long-standing practice, at least in the Netherlands. The Netherlands' Central Bureau of Statistics has drawn balances based on statistical and monitoring data since 1970. The balances regarding macronutrients also have chronological series. The metals balances have not been repeated to date. In the future, monitoring substance flows in this way will become more difficult because no more physical flow data will be collected for EU member states for the Eurostat Trade Statistics. It will not be easy to overcome this loss. So far, the use that has been made of these balances in environmental policy has been limited, or rather, they do not have the standard position they deserve. Suggestions have been made to add the state of the natural resources to the System of National Accounts. Keeping track of selected elementary resources could be a part of such an addition.

Footprint: the global environmental consequences of the consumption in a region
Considering the consequences of certain actions and policies on the national level for the rest of the world is becoming an issue of increasing importance. Substance policy makers also must be able to consider the consequences of their plans in a global perspective, in order to spot shifting of problems to other parts of the world. The conclusions that can be drawn from the *footprint* SFA application are therefore relevant. The design of indicators to measure policy performance with regard to this global aspect is strongly recommended. For this specific SFA application, the main problem lies in the availability and the amount of work that must be put into collecting and elaborating the data. In Chapter 4, the *pollution export* indicator is proposed in this respect. To avoid data problems, an escape route is presented by making use only of regional data. This limits the amount of effort required, but also limits the value of the outcome, possibly strongly.

Origins: the economic or environmental causes of pollution problems in a region
The origins analysis links pollution problems to their (mostly economic) origins. The distinction between the three levels of origins is useful and proves to be an addition to most analyses, because the exclusive definition of the levels prevents double-counts and applies to different policy target areas. For any pollutants policy it is a necessity to look into the causes of pollution. The SFA origins analysis is recommended in all cases where the causes are not apparent at first sight, i.e. whenever the substance has an economic life cycle worth mentioning.

Solutions: the comparison of the environmental consequences of different substance management regimes
The ability to scan potential solutions to determine their effectiveness and side-effects is an important asset for a substance policy. The *solutions* application of SFA provides a possibility to do so. However the limitations of this option must be kept in mind. The results must not be regarded as a prediction of a future situation, but merely as an indication of the solution working in the right direction and as a means of comparing different options. Moreover, when contemplating substitution of the substance in its applications, additional information is required with regard to the alternatives, such as is delivered by a product LCA, for example. Within these limits, the *solutions* application has proven to be very valuable in the case studies and the main source of information for designing a management strategy.

Predictions: the prediction of a future situation under certain assumptions

Reduction targets are mostly set for specific years in the future. Environmental forecasts refer to those years. Those forecasts provide one of the most valued sources for the design of environmental policy, and therefore it is important that these forecasts are as reliable as possible. Two major difficulties must be overcome in order to create a chance for reaching a sufficient level of reliability" the lack of dynamic substance flow models, and the lack of data regarding economic and environmental stocks. Without dynamic modelling and data on the economic stocks, the predictions are likely to be inadequate for substances with a complicated economic life cycle and/or a long economic life span of their applications.

10.3.3 The role of SFA in formulating a substance management strategy

The SFA tool has been primarily developed for analysis. However, it can also play a role in the development of substance management strategies. The SFA applications discussed above provide relevant input for the design of such a strategy. However, the results of a detailed SFA study are not available in all cases, and it is obviously impossible to indulge in detailed investigations for every substance that appears in economic processes. A streamlining of the SFA methodology could therefore be of great practical value for substance policy.

The development of substance management strategies is the subject of Chapter 6. The aim was to determine whether it would be possible to use general, easily available information on a substance as a basis for a management strategy. In Chapter 6, economic substance characteristics are formulated, based on physical/chemical and other substance properties on the one hand, and on qualitative data related to the economic applications on the other hand. These economic characteristics can be used to draw conclusions regarding the principal usefulness of general abatement measures in each specific case. A protocol is outlined that could be used to obtain a first rough draft for any specific pollutants policy. In this protocol, a list of ten general types of abatement options is checked against the economic characteristics of the substance to establish their usefulness in principle. Out of the useful options, a strategy outline can be built.

The general management strategy outlines for cadmium and nitrogen compounds, as put down in Chapter 6, are sketchy. However, the general outlines have the distinct advantage of being comprehensive (including all stages of the economic life cycle), and seem to avoid the three main mechanisms of problem shifting (within the substance chain, to other areas, and to the future). On a general level, they make sense and therefore may serve as guidelines for a more detailed substance management measure package. It seems possible, therefore, to make the connection between general, easily available substance data and the main directions for its management. It may even be possible to include large groups of substances, that have similar economic characteristics, in a general strategy. However, the concept of economic characteristics has not yet grown beyond the idea-stage. More thinking, and in due time more research, must be put into this idea to develop it further.

To fill in the details of a strategy, more information is required. An SFA study is not always needed, but is strongly recommended for substances with complicated pathways or a longer stay in the economy. All SFA applications, but especially the comparison of different regimes option, Provide relevant information. It should be kept in mind, however, that the "details" mentioned here concern only the technical details. A mature management strategy is concerned also with the choice for policy instruments, with implementation, with maintaining the rules, and with the evaluation afterwards. The role of SFA is limited here. As mentioned in Chapters 1 and 2, there are some ideas for linking the SFA, or suchlike, investigating procedure to specific substance-oriented policy instruments. The substance deposit system is such an instrument. This too is research territory still open for development.

A final issue of discussion concerns the practical use of SFA, and also other suchlike analytic tools, in support of environmental policy. It will not be possible to perform extensive SFA studies for every substance that is the subject of environmental policy. Likewise, it is impossible to conduct LCA studies for all relevant products, or risk assessment studies for every relevant situation. It is therefore important that both policy makers and environmental scientists involved in designing those tools also direct their attention to how to streamline the use of them. This streamlining may take various shapes:

- defining simplified versions of the tools
- defining general rules based on the patterns that arise out of the practical applications
- indicating in which cases which tools are required, and in which cases not.

The idea of taking the economic substance characteristics of substances as a basis for their management strategy is an example of the second type of streamlining. This may be a valuable route to explore in future. Other such routes may be identified as well. Failing to do so might serve to prevent the developed instruments in this field from being taken seriously, however valuable they are in principle.

10.4 Conclusions

Position of SFA:

1. SFA is one of the tools supporting integrated chain management. It is developed for the analysis of *substance* chains. Other types of chains, for example product chains, materials chains and mass chains, require other tools, with a different methodology and data requirements.

SFA methodology:

2. A framework consisting of three components is proposed:
- definition of the system
- quantification of the overview of flows and stocks
- interpretation of the results.

This framework may well serve as a general framework for all SFA applications. Thereby it can act as a means to bring more coherence in the SFA scientific field, which is at present very scattered.

3. The SFA system represents the substance chain from cradle to grave. Its definition starts from the substance choice (one substance or a coherent group of substances). Furthermore, the SFA system is defined with regard to space (a region), and time (a year), but integrates over all functions.

4. Two approaches can be followed to define the substance chain system:
- a regional approach, defining the system by its geographic boundaries
- a functional approach, taking the region's use or consumption (final demand?) as the starting point and specifying the cradle as well as the grave of this use, wherever it may take place.

The regional approach enables one to analyze pollution as it occurs within the given region. The functional approach aimes at specifying pollution occurring anywhere in the world for the fulfilment of functions for the region's population.

5. Three ways of quantifying the overview of the flows and stocks of a substance (group) are distinguished:

- bookkeeping
- static modelling
- dynamic modelling.

Bookkeeping is useful for monitoring the state of flows and stocks and the developments through time. Static modelling can be used for the analysis of the origins of pollution problems and for comparing different abatement options. Dynamic modelling is useful for forecasting and for scenario analyses.

6. Dynamic modelling can be regarded as more advanced than static modelling. Nonetheless, comparative static modelling - if applied in its proper place - has distinct advantages over dynamic modelling: the results are more robust, problem shifting to the future is eliminated, and the data demand is less extensive. Forecasting the future however should not be attempted with static modelling.

7. Data availability and quality vary with the substance. Data regarding stocks of substances, both in the economy and in the environment, are almost completely lacking. This is most problematical 'Or the dynamic type of modelling.

8. The combination of data into one coherent overview appears to serve as a powerful check and as a mute for data errors.

9. The interpretation of the SFA results (the overview of flows and stocks) can be attempted by linking quantity to quality, i.e., by linking the emissions and/or specific environmental flows to information regarding the harmful nature of the substance. Examples of such information include no-effect levels, equivalency factors and policy targets. This makes it possible to evaluate, or at 'east to compare, different overviews on their environmental consequences.

'0. Another way of interpreting the SFA results is the definition of indicators for integrated substance chain management. For a more or less complete set, to be used for an overall evaluation °f a substance management regime, four categories of indicators are distinguished:

- depletion indicators, in terms of the established depletion problems
- pollution indicators, in terms of the established pollution problems
- indicators in terms of the substance management in the (physical) economy
- indicators for problem shifting, either to other parts of the SFA system, to the future, or to other regions.

11. The SFA methodology enables the user to trace the origins of specific pollution problems on toree levels:

- the direct causes or the immissions
- the economic sectors directly responsible for the emissions causing the problem
- the ultimate origins on the border of the SFA system: the system's sources.

fcach level provides relevant information for policy makers. Separating the levels may prevent unnecessaryinconsistencies.

Case studies

12. The cadmium pollution problems can be traced back to two major sources: phosphate rock and zinc ore.

13. Almost 70% of the 1987 inflow of cadmium appears to accumulate in the economic system. This stockbuilding indicates a risk for a future increase in emissions.

14. The generally accepted notions of source-oriented policy and recycling do not appear to work in the case of cadmium. This is caused by the inelastic nature of the cadmium supply, because of which a diminished demand does not lead to a decreased supply. A cadmium policy therefore should address the ultimate sources on the one hand, and concentrate on waste immobilization on the other.

15. Different nitrogen related environmental problems in the EU can be traced back to a single most important source: the industrial N_2 fixation for the production of fertilizer. Neither the agricultural overproduction in the EU, nor the import of fodder appear to be important causes of the N-related problems.

16. The solution of all N-problems and the current EC agricultural production appear to be incompatible, even when a maximum package of technical abatement measures is presupposed. Either very drastic changes are required in both food production and consumption, or the environmental targets must be set less strictly.

Value of SFA for environmental policy

17. SFA can play a role in environmental substance policy in analyzing the connection of the economy with the environment in a physical sense. By doing so, it becomes possible to link environmental problems to their origins, and to estimate the effectiveness of certain abatement measures as well as the occurrence of problem shifting connected with these measures.

18. Five specific SFA applications are distinguished:

- *state:* the evaluation of the situation in a given region in the present or recent past
- *footprint*: the evaluation of the worldwide environmental consequences of the consumption in a given region
- *origins:* establishing the economic or environmental causes of specific pollution problems along the chain of physical causality
- *solutions:* the comparison of different substance management regimes on their environmental consequences
- *predictions:* the prediction of a future situation under certain assumptions.

All applications fall within the general SFA framework described above. In addition, they all have their own, specific requirements regarding the system's definition and the appropriate type of modelling.

19. The applications *state, origins* and *solutions* are sufficiently worked out for practical application in support of environmental substance policy. Both *footprint* and *predictions* require further methodological development.

20. The use of SFA is particularly required in cases of substances with a relatively complicated economic life-cycle and/or application in durable products.

21. Based on the experience of a number of SFA studies, a number of *economic characteristics* have been described, which can be regarded as inherent properties of the given substances. These economic characteristics can be used as the main input for sketching an outline of a substance management strategy.

10.5 Recommendations

Recommendations for further research

1. **Regarding the SFA *system's definition* the most important scientific discussion is related to the dependency of it on the specific questions that must be answered by the SFA study, or in other words on the specific SFA application. Separating the functional from the regional angle would clarify much already.**

2. With regard to the *quantification of the overview* there are several important issues:
   - data availability and quality: for SFA applications on the level of EU member states, repairing the recent quality loss of the trade statistics is a problem that needs to be solved. A second issue is the lack of data on economic and environmental stocks. Investigating these more carefully is recommended strongly in order to create one of the necessary conditions for scanning potential futures.
   - modelling: attention for the development and implementation of dynamic substance flow modelling is recommended, although at the same time its overall importance may be somewhat questioned. Another issue is the inclusion of economic causality in the modelling. As yet, the economic causality is limited to the basic decision regarding whether the model should be supply-driven or demand-driven. It would certainly be useful to try to put more of economic modelling into SFA for the applications *solutions* and *predictions.*
   - evaluation of the quantification step: the development of a standard procedure of sensitivity analysis, to be conducted for every case study, is recommended strongly as well. In time, incorporating a procedure for handling data inconsistencies within the system may be preferred to a separate sensitivity analysis.

3. For the *interpretation of the results,* the link of the SFA outcome with existing evaluation systems - risk assessment models, or an evaluation procedure such as is used in some of the LCA studies - should be worked out further. In that way, the SFA results can be translated into policy relevant terms. Another recommendation is the further development of indicators to characterize integrated chains of the various types (mass, product/function, material, and substance), by which the general goals of integrated substance chain policy can be measured.

4. Another direction of development concerns the *linking of SFA to other types of models.* On the input side, a link - which does not necessarily have to be a computerized link - can be imagined with economic scenario models, of which the output could be an input for an SFA model. On the output side, a link with existing environmental fate models can be considered. A link to a general multimedia model can be envisaged. A link with environmental models with a spatial dimension (e.g., GIS-based models) could be considered in order to be able to link some of the environmental flows and stocks to specific geographic locations. This, however, requires careful deliberation to determine if, and how, such a step can be taken. Finally, the link to an economic evaluation system would be relevant, so that the physical changes could be matched with monetary changes Adding this dimension would also open possibilities for optimizing measure packages with regard to costs.

5. A final recommendation concerns the scientific attention for the *streamlining of the SFA tool.* It is a scientific task not only to develop sophisticated models and tools, but also to indicate in which cases policy can do without them or could make use of simplified versions, limited datasets or only of qualitative information regarding substance properties and applications.

Recommendations for the use of SFA in environmental policy

6. A first recommendation is making more use of the already existing *state* application for following the state of flows and stocks over the years. Not all substances, but a careful selection of important ones from an environmental point of view, which also have a relatively complicated economic life cycle and/or a relative longevity, might be considered. Examples are: metals, nutrients, carbon, sulphur, and halogenated organic compounds. This may be contemplated as a part of a Natural Resource Accounting system.

7. When formulating general management strategies for (groups of) substances, the *origins* and the *solution* application provide important information, which can hardly be obtained by other means. Especially when a bookkeeping overview is present, this SFA application is available already and can be used for policy supporting purposes as it is.

8. The international and global aspects of a region's integrated substance chain management are relevant as well, and will become more important in the years to come. Both for this application, the *footprint*, as well as for the *prediction* application which could be used in scenario analyses, the outline is there but the SFA application is insufficiently developed for general use. It is very much in the interest of environmental policy to stimulate this further development and maturing of the SFA instrument and not to leave this altogether to the caprices of scientists. It is perhaps the only way that environmental policy can actually influence the direction of this development, and consequently, the possibilities for them to make use of the tool.

10.6 Some final remarks

A major task for environmental science is the development of methodologies to support environmental policy. The integrated chain management is one of the areas of environmental policy of growing importance. The aim of this thesis has been to contribute to the development of one of the analytical instruments for the support of integrated chain management: SFA, the analysis of substance flows through the society and the environment. It can be concluded that SFA, if applied in its proper place, may contribute significantly to both the formulation and the evaluation of environmental policy related to substances. Environmental problems can be traced back to their economic origins, and substances used in the economic system can be followed to their final destination in the environment. On the one hand, the SFA tool can be developed further in order to enhance its policy supporting qualities. On the other hand, it is important that SFA find its proper place among the other tools for integrated chain analysis, such as LCA and MFA. For every such tool, the limitations are as important as the possibilities. Developing a set of tools in harmony would serve environmental policy much better than trying to promote a single tool capable of encompassing all aspects of integrated chain management. Here lies one of the major challenges for environmental science for the future.

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CURRICULUM VITAE

Ester van der Voet was born in 1956 in Amsterdam. She graduated from the Gymnasium Haganum in The Hague in 1974. Since it was, at that point in time, not possible to study environmental science, she studied biology at Leiden University. Major subjects were: plant systematics, evolutionary biology, and of course environmental science. She graduated in 1981. Her first job as an environmental scientist, in 1982, was with the Centre of Energy Conservation and Clean Technology at Delft, where she contributed to the ongoing "broad societal discussion" regarding energy generation options by comparing the environmental impacts of the various scenarios.

In 1984, she came to work for her current employer, the Centre of Environmental Science of Leiden University, as a project researcher on the subject of intensive stockbreeding and the environmental problems related to ammonia. She contributed to the currently practiced Regeling Veehouderij en Ammoniak, wherein the environmental conditions for permits for stockbreeding firms is regulated, as well as to the so called object oriented policy for ammonia.

In 1989 she became a project leader for projects mainly in the area of substance-related environmental problems and substance policy. Other subjects of investigation have been, among others: resource management, natural resource accounting, and biodiversity policy. Since 1991, she has combined her Ph.D thesis work on Substance Flow Analysis, financed by NWO, with the project leader work at the Centre of Environmental Science. Now she is a full time project leader again.

APPENDICES

APPENDIX 1 SENSITIVITY OF BOOKKEEPING AND MODELLING SYSTEMS

Appendix 1 refers to the second element of the general SFA framework: the quantification of the overview of flows and stocks. The aim of this appendix is to obtain an insight in two aspects of the quantification procedure:

1. The influence of several choices regarding the modelling setup that must be made during the procedure
2. The influence of uncertainties in data on the quantification result.

In order to achieve this aim, the sensitivity of two simple systems is tested with regard to the setup of the quantification procedure. The sensitivity for uncertainties - and therefore also for changes in regime - of these two systems is tested for the bookkeeping system and the model. Within the model option, the influence is tested of

- variations in the distribution coefficients
- the magnitude of the fixed variables on the overview
- the influence of choosing different parameters as the system's fixed variables.

In Section 1 of this appendix, the very small system EXAMPLE, also used in Chapter 3, is introduced once again. Here, the various choices that must be made when translating a bookkeeping system into a model are treated. In Section 2, the system SIMPLE is defined. This system is somewhat larger than EXAMPLE and has a little more connection to reality. It represents flows of nitrogen in an imaginary area. On this system a marginal analysis (Heijungs, 1995) is performed, mainly to test the difference in reaction between a bookkeeping system and a model, but also with regard to the influence of (a) the balancing formulas, and (b) the choice for the fixed variables.

1 The system EXAMPLE

The system EXAMPLE is used in Chapter 3 to clarify the theoretical explanations regarding the modelling of substance flows. Because it is a very small system, it can be used to test some aspects of the choices that must be made when modelling a system of substance flows and stocks. In this section, the goal is not to test margins of error in the data, but to test the influence of the choices that can be made regarding the translation of the bookkeeping system into the model. In Figure A1.1, EXAMPLE is pictured once again.

The first derivations from EXAMPLE are two models for the reference year, EXIMPLE1 and EXIMPLE2. In these models, the bookkeeping data are translated into distribution coefficients in two different ways: calculating the outflows of a node as a fraction of the totalized inflows (including the stock) (EXIMPLE2), and by differentiating more between the different inflows and toe stocks in an attempt to include as much physical causality as possible (EXIMPLE1). The outcome for the reference year is, of course, in both cases identical to EXAMPLE. In both cases, the system's sources (x1 and x2) are appointed as the fixed variables, on which the other flows and stocks depend. The set of equations for both systems is presented below:

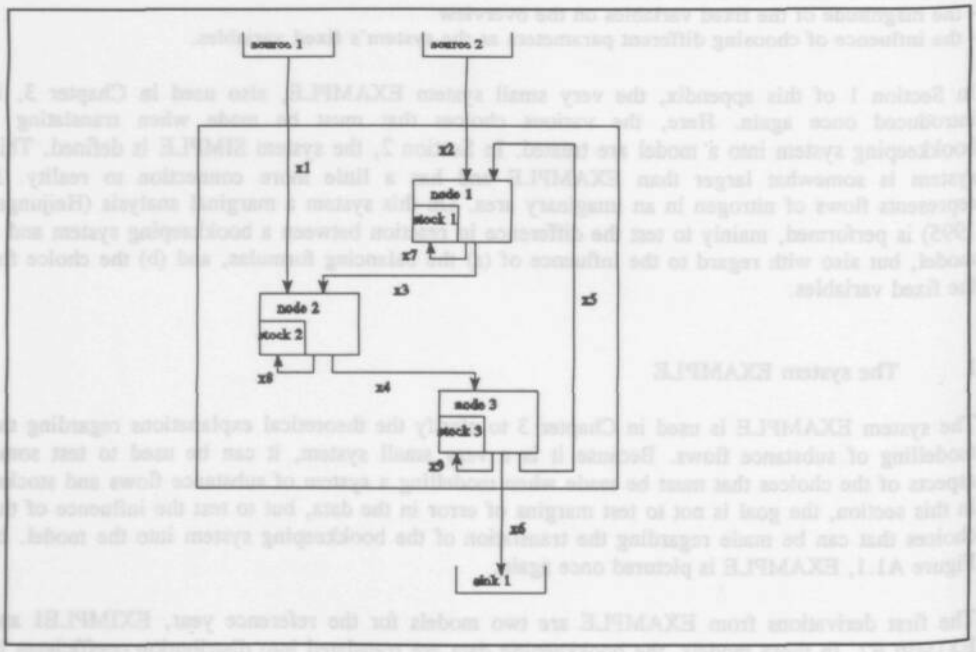
EXIMPLE1

$x_1 = 20$
$x_2 = 100$
$x_3 = 0.045 * s_1$
$x_4 = 0.2 * (x_1 + x_3) + 0.36 * s_2$
$x_7 = 0.7 - s_3$
$x_6 = 0.8 * x_4$
$x_8 = -0.2 - s_2$
$x_2 + x_5 - x_3 = 0$
$x_1 + x_3 - x_4 - x_8 = 0$
$x_4 - x_5 - x_6 = 0$

EXIMPLE2

$x_1 = 20$
$x_2 = 100$
$x_3 = 0.043 * (x_2 + x_5 + s_1)$
$x_4 = 0.336 * (x_1 + x_3 + s_2)$
$x_5 = 0.1498 * (x_4 + s_3)$
$x_6 = 0.6367 * (x_4 + s_3)$
$x_8 = -0.2 * s_2$
$x_2 + x_5 - x_3 = 0$
$x_1 + x_3 - x_4 - x_8 = 0$
$x_4 - x_5 - x_6 = 0$

Figure A1.1 The system EXAMPLE



Because the system is out of balance, the long term steady state situation will differ from the situation in the reference year. Five different ways of calculating the steady state situation belonging to the reference regime have been attempted, each starting from the situation described in EXAMPLE:

1. **TEXIMPL1,** using the EXIMPLEl file and eliminating x7 and its formula.
2. **TEXIMPL2,** using the EXIMPLE2 file and eliminating x7 and its formula, to establish the influence of different distribution factors regarding the same inflows and outflows.
3. **TEXIMPL3,** using the EXIMPLEl file, eliminating x7 and its formula, but also eliminating the system's stocks, to establish the influence of the stocks on the steady state flows.

4. TEXIMPL4, using the EXIMPLE1 file, eliminating x7 and its formula, making the use flow or demand (x3) a fixed variable instead of x2, to establish the influence of the introduction of another type of causality — in this case economic causality rather than physical causality.

5. TEXIMPL5, similar to TEXIMPL4 but this time appointing the user's stock s2 as the fixed variable instead of x3, as another variant of economic causality.

In the table below, the results of the calculations are presented. The fixed variables are presented in italics.

Table A1.1 Results of different modelling parameters based on one starting situation

	EXAMPLE*	TEXIMPL1	TEXIMPL2	TEXIMPL3	TEXIMPL4	TEXIMPL5
			= = the system's inflows = =			
x1	20	*20*	*20*	*20*	*20*	*20*
X2	100	*100*	*100*	*100*	142	365
			== the system's internal flows = =			
x3	180	128	128	128	*180*	455
X4	420	148	148	148	200	475
X5	80	28	28	28	38	90
			= = the system's outflow = =			
x6	340	120	120	120	162	385
			= = the system's accumulation = =			
X8	-220	-	-	-	-	-
			= = the system's stocks = =			
s1	4000	2850	2850		4000	10111
s2	1050	328	293		442	*1050*
S3	114	40	40		54	129

* EXAMPLE represents the starting situation, EXIMPLE1 and EXIMPLE2 render an identical overview with the system's inflows as fixed variables.

All of the steady states of EXAMPLE differ markedly from EXAMPLE. The three files with fixed sources, TEXIMPL1, TEXIMPL2 and TEXIMPL3, show identical flows. From this, it can be concluded that, as argued in Chapter 3, the nodes' outflows in the steady state situation are not determined by the stocks' magnitude but by the nodes' inflows, according to IN = OUT. TEXIMPL1 and TEXIMPL2 only differ with regard to stock s2. It would therefore appear that different distribution factors, if derived from a bookkeeping overview in a starting year, have no great influence on the steady state situation. This could be different for the dynamic option, where calculating the situation in years between now and eternity is relevant. The statement made in Chapters 3 and 4 that the long term steady state offers the best possibilities for comparing different regimes if information regarding the stocks is lacking, is supported strongly by this. The assumptions made in the process of deriving the technical distribution coefficients have some influence, but the difference is not very large, as can be seen when comparing TEXIMPL1 with TEXIMPL2. All three cases of fixed inflows lead to a lower level for both flows and stocks (if applicable) compared to the starting situation as described in EXAMPLE.

The choice for the fixed variables on the other hand appears to have a large influence on the flows and stocks. If, as is the case in TEXIMPL4, it is assumed that x3 is constant rather than x2, the

steady state situation has much larger flows and stocks, although generally still on a lower level than in EXAMPLE. Assuming stock s2 to be constant, as is the case in TEXIMPL5, leads to still larger flows and stocks, in this case even larger than in the starting situation EXAMPLE!

Also of interest is the influence of these different assumptions on the effectiveness of certain regime changes. To test this, one regime change is implemented in all five TEXIMPL files: a change in the fixed inflow x1. This variable, fixed at 20 units, is brought down to 0 and elevated to SO units in all TEXIMPL files. The table below shows the impacts of this change, with again the fixed variables in italics.

Table A1.2 The impacts of changes in xl on the system's steady state flows and stocks

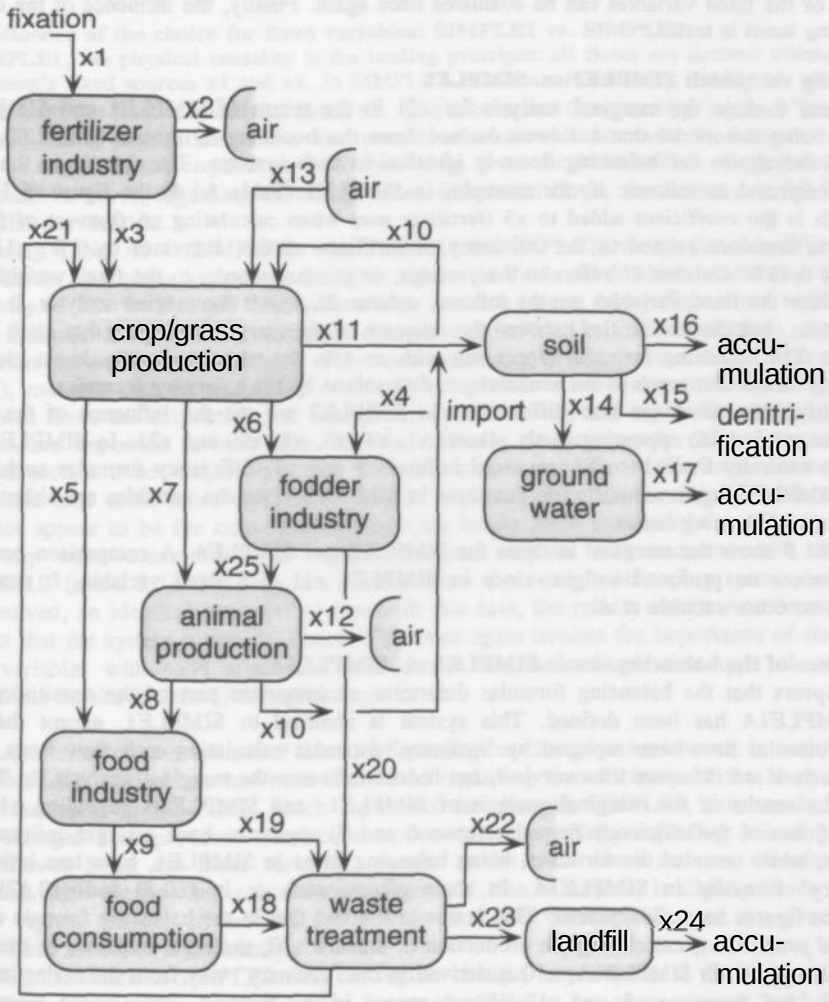
	TEXIMPL1		TEXIMPL2		TEXIMPL3		TEXIMPL4		TEXIMPL 5	
					= = the system's inflows = =					
xI	*0*	50	*0*	*50*	*0*	*50*	*0*	*50*	*0*	*50*
x2	*100*	700	*100*	*100*	*100*	*100*	146	136	385	335
					= = the system's internal flows = =					
x3	123	135	123	135	123	135	780	*180*	475	425
x4	123	185	123	185	123	185	180	230	475	475
x5	23	35	23	35	23	35	34	44	90	90
					= = the system's outflow = =					
x6	100	150	100	150	100	150	146	186	385	385
					= = the system's stocks = =					
s1	2745	3007	2745	3007	-		4000	4000	10556	9444
s2	273	410	244	366	-		398	508	7050	7050
s3	34	50	34	50			49	62	129	129

Again it appears that the choice for the fixed variables has the greatest impact. TEXIMPL1, 2 and 3 show identical reactions to the change: all flows and stocks go up and down with x1. TEXIMPL4, with the fixed x3, shows a compensation mechanism: when xl is lowered, x2 increases. This is even more apparent in TEXIMPL5, where the changes in xl are compensated for fully by counterchanges in x2, leaving the outflow x6 at exactly the same level of 385. In TEXIMPL4, x3 (naturally) and also s1 remain at the same level, but x4, x5 and x6 as well as s2 and s3 increase together with x1. In TEXIMPL5 this is not the case: both x2 and x3 decrease when xl increases, as does the stock s1. The other flows and stocks do not change.

This means that the choice for the fixed variables is very important when calculating the impacts of certain measures or measure packages. Variations in the distribution coefficients do not seem *to* cause any differences, as is illustrated by TEXIMPLs 1 through 3. Alterations in the choice *for* the fixed variables may however lead not only to differences in the magnitude of the figures, but even to contradictory results regarding the direction in which the changes work: in one case a lower level of flows and stocks can be detected, while in another a higher level of flows and stocks shows as the result of an identical measure.

The system SIMPLE, pictured below as Figure A1.2, represents flows of nitrogen through an imaginary area. The economic nodes refer to processes of food production and consumption, the environmental nodes to soil, air, groundwater and landfill sites. There are 25 flows and no stocks in the system. The economic part of the system, having a turnover time of one year, is balanced. Therefore, any uncertainties arising from deviations from the equilibrium situation are excluded. Three loops can be distinguished: the use of animal manure, the use of compost, and the atmospheric deposition on agricultural soils. The magnitude of the flows x1 to x25 is shown in Table A1.3.

Figure A1.2 The system SIMPLE



For the imaginary reference year, the flows are assumed to be based on statistical and monitoring data. Derived from that are four different SFINX files. SIMPLE1 is a model, with the system's sources (x1 and x4) as fixed variables. SIMPLE2 is also a model, with the demand for food and the import of fodder (x9 and x4) as fixed variables. SIMPLE3 and SIMPLE4 are bookkeeping systems, with different choices for the balancing items.

The influence of the model's fixed variables, the distribution coefficients, and the balancing items on the outcome are tested by performing a so called marginal analysis (*Heijungs, 1995*). In this analysis, the influence of changes, both in the distribution coefficients and in the fixed variables, on the outcome for a specific flow are determined. For this, a specific flow x11, the nitrogen surplus in agricultural soil, has been chosen, since most of the environmental flows are derived from this flow. By performing this analysis for the four different options, an insight is gained into the differences in reaction between a bookkeeping system and a model. Moreover, the influence of the choice of the fixed variables can be evaluated once again. Finally, the influence of the choice for balancing items is tested.

Bookkeeping vs. model: SIMPLE3 vs. SIMPLE1

Tables 4 and 8 show the marginal analysis for x1l in the setups of SIMPLE1 and SIMPLE3, SIMPLE1 being the model that has been derived from the bookkeeping system SIMPLE3. This means that the choice for balancing items is identical in both systems. The figures in the table must be interpreted as follows: if, for example, in SIMPLE1 (Table A1.4) the figure (6,3) of -0.15, which is the coefficient added to x3 (fertilizer use) when calculating x6 (harvest of fodder crop) and is therefore related to the efficiency of fertilizer uptake, increases by 1%, x11 will decrease by 0.15%. Column 26 refers to the y-vector, or in other words, to the fixed variables. In the case where the fixed variables are the inflows, column 26 equals the origins analysis. It is not the differences, but the similarities between the outcome of the marginal analysis that catch one's eye at first. The balancing formulas (appearing with an * in the tables) provide almost identical figures. This means that much of the sensitivity is determined by the balancing formulas.

Besides similarities, there are also differences. In SIMPLE3 we see the influence of the fixed variables (in column 26) appearing in six places: x1, x4, x5, x8, x20 and x21. In SIMPLE1 this influence is naturally limited to the two fixed inflows xl and x4. Efficiency formulas such as in row 6 of SIMPLE1, again naturally, do not show in SIMPLE3 since the variables are either fixed or calculated as balancing items.

Tables 6 and 9 show the marginal analysis for SIMPLE2 and SIMPLE4. A comparison between the two renders no profound insight, since in SIMPLE4 x11 is a fixed variable. It therefore depends on no other variable at all.

The influence of the balancing items: SIMPLE1 vs. SIMPLE1A

Since it appears that the balancing formulas determine an important part of the sensitivity, the system SIMPLE1A has been defined. This system is identical to SIMPLE1, except that the balancing formulas have been replaced by "ordinary" formulas calculating each flow from other flows. This does not influence the overview, but it does influence the marginal analysis. In Tables 4 and 5, the results of the marginal analysis of SIMPLE1 and SIMPLE1A regarding x1l are presented. Some of the efficiency formulas (rows 6 and 7) appear to have a larger influence in SIMPLE1A, while some of the formulas, being balancing items in SIMPLE1, have less influence as "ordinary" formulas in SIMPLE1A. In some places, such as in (10,8) and (10,12), for example, the figures have disappeared. This is due to the fact that in the balancing formula of the node *animal production*, calculating the production of manure x10, the other outflows of the node (x8 and xl2) appear. In SIMPLE1A, xlO is derived in the "ordinary" way from the nodes inflows x7 and x25, and therefore x8 and xl2 do not appear in the formula. This would mean that SIMPLE1A is most representative of reality, i.e. in this case physical causality: in the real world,

the N surplus in soils would be affected much more by the uptake efficiencies than by the distribution of the animal production over the various outflows.
Oddly enough, there are also differences that point in another direction. For example the formula determining x5, appearing in row 5, seems to have a larger influence on x11 in SIMPLE1 than in SIMPLE1A, although the formulas are identical in both files. The same applies to row 20. This can only be explained by assuming that in SIMPLE1 somehow, through the balancing formulas, these formulas have an unduly high influence.

Analogously SIMPLE2A is defined as SIMPLE2 without balancing formulas. The conclusions that can be drawn from comparing SIMPLE2 with SIMPLE2A (tables 6 and 7) are rather similar. Here, the influence on x11 of the formula calculating x7 (a balancing item in SIMPLE2) seems to be lower in SIMPLE2A. Row 25, on the other hand, has much higher figures in SIMPLE2A, although the formula is identical in both files.

The influence of the choice for fixed variables: SIMPLE1 vs. SIMPLE2

In SIMPLE1 the physical causality is the leading principle: all flows are derived ultimately from the system's fixed sources x1 and x4. In SIMPLE2 an economic causality is adopted: all flows are derived from the fixed demand for food, x9. This means that the causality "upchain" is reversed, of course taking physical causalities into consideration as well (so much food requires so much harvested crop, and this requires so much fertilizing, given the technicalities of uptake efficiency). Downchain however, regarding the waste and environmental flows, the formulas m SIMPLE1 and SIMPLE2 are identical.
Comparing Table A1.4 (SIMPLE1) with Table A1.6 (SIMPLE2) shows that the differences are large. In the first place we see much higher figures in Table A1.6 which means that the overall sensitivity of x11 for changes c.q. uncertainties is much larger. Many figures are higher than 1, which indicates an intensified impact of changes c.q. errors. In the second place, the sensitive parameters are almost all different. There are some similarities on the diagonal axis (1,1) to (25,25), meaning that the magnitude of the flows themselves have some influence regardless of how these flows are calculated. For example x3 (fertilizer use) and especially x10 (application of manure) are important in both files. For the formulas determining the upchain processes, the different picture is not surprising, since these are completely different formulas. However m the downchain area some more similarity could be expected since the formulas are identical. This does not appear to be the case. The two systems hardly seem comparable at all and react very differently when confronted with regime changes, such as also occurred with the system EXAMPLE (see 1 2 1). Yet they are derived from the same bookkeeping system, and render, when solved, an identical overview of flows. In this case, the results cannot even be attributed to the fact that the system is out-of-balance. This once again stresses the importance of choosing the fixed variables with solid arguments, and determining beforehand what type of causality is appropriate for the desired SFA application.

Table A1.3 shows the overview of flows, when a regime change is introduced. In both SIMPLE1 and SIMPLE2, an increase has been introduced regarding the efficiency of the N uptake in the crop/grass node. In SIMPLEl, which represents the changed SIMPLEl this results in a very much enlarged food production and consumption cycle, especially regarding animal production. The inflows, being the fixed variables, remain at the same level and so therefore, do the combined denitrification and accumulation. Since x11, the N surplus, is slightly lower as a result of the regime change, so are the groundwater and soil accumulation and the denitrification. Landfill has increased significantly.
In SIMPLEII which is SIMPLE2 with the regime change, consumption is the fixed variable, and therefore remains at the same level. The increased efficiency has consequences "upchain mainly for x3, the fertilizer use, which has decreased enormously. Since the required crop/grass

production is unchanged, x11 has been halved, and so, therefore, have the concurrent environmental flows. "Downchain" from the crop/grass production, everything - even animal, food and fodder production - is unchanged.

Table A1.3 **The system SIMPLE with increased crop uptake efficiency, calculated according to SIMPLEI and SIMPLEII**

	SIMPLE (SIMPLE1-4)	SIMPLEI	SIMPLEII
x1	722	722	335
X 2	4	4	2
X3	718	718	333
X4	30	30	30
X5	62.5	130	62.5
X6	361	751	316
X7	312.5	652	312.5
x8	62.5	128	62.5
x9	100	206	100
x10	500	1021	500
x11	571	383	184
XI2	62.5	128	62.5
X13	68	135	66
X14	143	96	46
X15	143	96	46
X16	286	192	96
XI7	143	96	46
X18	100	206	100
X19	25	52	25
x20	78	156	78
X21	20	41	20
x 2 2	2	4	2
X23	181	369	181
X24	181	369	181
X25	312.5	625	312.5

In this case, it is obvious that SIMPLE2, set up according to the economic demand causality, is the best choice if the aim is to estimate the impacts of regime changes on the overview of flows and stocks. People will not start eating more or differently because the agricultural efficiency increases. Demand represents the best candidate for selection as the fixed variable, and the supply may be expected to react to regime changes rather than the demand. This, however, is not so clear in all cases. Sometimes the demand will be more elastic. In other cases, the supply will be inelastic, such as in the case of cadmium. The possibility of import and export complicate the picture even more. Other purposes may require another modelling setup; the origins analysis for example can only be performed with the system's sources as fixed variables. The message derived from this is that the choice for the fixed variables must be made carefully, in relation to the aim of the analysis, in relation to the economic characteristics of the substance as they are delineated in Chapter 6, and in relation to the scale level of the analysis.

3 Conclusions

In this section, the influence on the modelling results of different options regarding the main choices that must be made when translating a bookkeeping system into a model was evaluated with the help of two examples. The options include:

- the choice for balancing items
- the derivation of distribution coefficients from the bookkeeping overview
- the choice for the fixed variables
- the difference between a bookkeeping system and a model in reaction to data variations and regime changes respectively.

It appears that the balancing items are responsible for an important part of the system's sensitivity to changes. Since every node has one in SFINX, a rather large part of the equations is balancing equations, both in the bookkeeping option and in the modelling option. The similarities between SIMPLE1 and SIMPLE3 illustrate this. This also implies that the difference in reaction between a bookkeeping system and a model can be less pronounced than might be expected.

The distribution coefficients, although they are the principle characteristics of the processes involved, are less important than one might imagine beforehand. In calculating the steady state situation, different ways of expressing a node's outflow as a function of the inflows do not result in different overviews in the EXAMPLE system, as can be seen from comparing TEXIMPL1, 2 and 3. When setting up a dynamic model, or using a static model to calculate changes in the manner of the National Environmental Outlook (i.e., without applying this to the steady state situation, such as has been done in the cadmium case study), this may be different again.

The choice for the fixed variables appears to be of crucial importance. In both EXAMPLE and SIMPLE, regime changes (or data errors) resulted in completely different reactions when different variables were appointed as the fixed ones, and this means not only differences in the absolute figures but also differences in the direction of the changes. It would appear that this is perhaps the most critical issue when translating an overview into a model.

When considering the case studies of cadmium and nitrogen in the European Union, discussed in Chapters 7 and 8, in this light, it can be concluded that the results of the nitrogen case study are in all probability more robust than those of the cadmium case study. In the first place, the deviation from the steady state situation is much larger in the case of cadmium, where roughly 70% of the inflow into the economic system accumulates. Cadmium is included in many different products with widely varying and moreover unknown life spans, while nitrogen is confined for the most part to the agricultural system, with a turnover of 1 year. Secondly, the steady state situation has been used to compare the different regimes in the nitrogen case study, but not in the case of

cadmium. It has appeared from the EXAMPLE calculations once again that in the steady state some uncertainties, especially with regard to the stocks' influence on the flows, are excluded. Thirdly, the choice for fixed variables is more difficult to make for cadmium, although arguments can be and have been found. For nitrogen, the most sensible choice would obviously be, and has in fact been, the use flow or demand, since the demand for food products in general, and more specifically proteins, is inelastic. In the case of cadmium, the inelasticity is on the supply side, because of its recovery as a byproduct of zinc, which would be an argument to support the choice made in the case study, for the system's inflows as the fixed variables. On a smaller scale level, of the Netherlands, for example, where imports and exports are large compared to the primary production, rather than the European Union, this argument would not be valid. In such a case, it would perhaps be better if the use flows or even the required users stocks were assigned as the fixed variables. Even on the EU level, imports and exports of cadmium and cadmium products - although relatively small - somewhat obscure the picture. In Appendix 2, the cadmium case study, including this aspect, will be addressed. The nitrogen case study is evaluated in Appendix 3.

4 References

Heijungs, R. On the identification of key issues for further investigation in life-cycle screening - the use of mathematical tools and statistics for sensitivity analysis. Paper for the Invitational Expert Seminar on Uncertainty and Statistics for product LCA, Delft, 23 May 1995.

Table A1.4 Marginal analysis for SIMPLEl: sensitivity of x11 for changes in the system's set of equations

A1.4a Set of equations

SIMPLM SI A

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	y
x1	1																									722
x2	-.005	1																								0
x3	-1	1	1																							0
x4				1																						30
x5		-.0595			1					0?<>75		-.0595								-.0425						0
x6		-.343				1				-.1715		-.343								-.245						0
x7		-.2975					1			-.14875		-.2975								-.2125						0
x8								1	1															-.1		0
x9					-1			-1	1										1							0
x10							-1	1		1		1												-1		0
III			-1		1	1	1			-1	1		-1								-1					0
x12							-.1					1													-.1	0
x13		-1									-1	1										-1				0
x14										-.25			1													0
x15										-.25				1												0
x16										-1			1	1	1											0
x17													-1	.		1										0
x18									-1								1									0
x19					-2			-2										1								0
x20				-2		-2													1							0
»21																		-.1	-.1	-.1	1					0
x22																		-.01	-.01	-.01		1				0
»23																		-1	-1	-1	1	1	1			0
x24																								-1	1	0
»25				-1		-1														1					1	0

A1.4b Marginal analysis

*T:\SIMPLE.MMO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	M	25	26
1-0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97
2 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3 0.97	0.00	-0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 0.00	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
5 0.00	0.00	-0.07	0.00	0.10	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6 0.00	0.00	-0.15	0.00	0.00	0.22	0.00	0.00	0.00	0.00	-0.05	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 0.00	0.00	0.00	0.00	0.00	0.00	0.M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.M	0.00
9 0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 0.00	0.00	0.00	0.00	0.00	0.00	0.48	-0.10	0.00	-0.77	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	
11 0.00	0.00	1.26	0.00	0.11	-0.63	0.55	0.00	0.00	0.88	-1.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O W	0.00	0.00	0.00	0.00	0.00
12 0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00
13 0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15 0.00	0.00	0.00	0.00	0.00	0.00	C 00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20 0.00	0.00	0.00	•0.01	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00
21 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	•0.03	0.00	0.00	0.00	0.00	0.00
22 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00
23 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00
24 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25 0.00	0.00	0.00	O.M	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.11	0.00	0.00	0.00	0.00	-0.43	0.00

Table A1.5 Marginal analysis for SIMPLE1A: sensitivity of x11 for changes in the system's set of equations

A1.5a Set of equations

SIMPLE1A.SFA

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	y
x1	1																									722
x2	-.005	1																								0
x3	-.995	0	1																							0
x4				1																						W
x5			-.0595		1					-.02975		-.0595								-.0425						0
x6			-.343			1				-.1715		-.343								-.245						0
x7			-.2975				1			-.14875		-.2975								-.2125						0
x8								1	1																-.1	0
»9					-.S			-.8	1																	0
»10							-.8			1															-.8	0
»11			-.3							-.M	1		1							-.5						0
x12							-1					1													-.1	0
x13		-1										-1	1								-1					0
x14											-.25			1												0
x15											-.25				1											0
x16											-.5					1										0
x17													-.1				1									0
x18									-1									1								0
x19					-.2			-.2											1							0
»20				-.2		-.2														1						0
»21																		-.1	-.1	-.1	1					0
»22																		-.01	-.01	-.01		1				0
x23																		-.89	-.89	-.89			1			0
»24																							-1	1		0
»25				-.8		-.8																			1	0

A1.5b Marginal analysis

*T:\SIMPLE1A.MMO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.06	0.00	0.96	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
5	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.28	0.00	0.00	0.41	0.00	0.00	0.00	0.10	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.30	0.00	0.00	0.00	0.43	0.00	0.00	0.10	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00
11	0.00	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.57	1.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
25	0.00	0.00	0.00	0.01	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

Table A1.6 Marginal analysis for SIMPLE2: sensitivity of x11 for changes in the system's set of equations

A1.6a Set of equations

SIMPLE2.SFA

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	y
x1	1	-1	-1																							0
x2	-.005	1																								0
x3			1		-1	-1	-1			1	-1		1								1					0
x4				1																						30
x5					1				-.5										-.5							0
>6				1		1														-1					-1	0
x7							1	-1		-1		-1													1	0
x8					1			1	-1										-1							0
x9									1																	100
x10							-.8			1															-.8	0
x11			-.3							-.65	1		-.3								-.5					0
x12							-1					1													-.1	0
x13		-1										-t	1										-1			0
x14											-.25			1												0
x15											-.25				1											0
X16											-1			1	1	1										0
x17														-1			1									0
III									-1									1								0
x19					-.2			-.2											1							0
«20				-.2		-.2														1						0
x21																		-.1	-.1	-.1	1					0
x22																		-.01	-.01	-01		1				0
x23																		-1	-1	-1	1	1	1			0
x24																							-1	1		0
«25								-5																	1	0

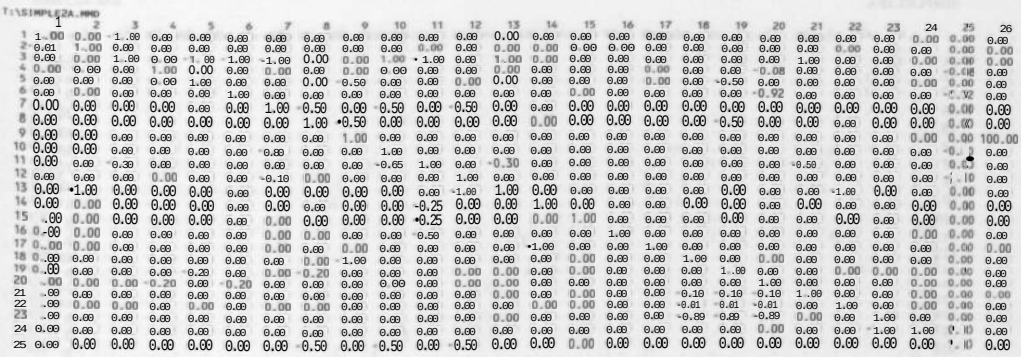
A1.6b Marginal analysis

*T:\SIMPLE2.MMO

	1	2	3	4	5	6	7	8	9	10	11	12	13	LI	15	16	17	18	19	20	21	22	23	24	25	26
1	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
2	0.00	0.00	0-00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	-0.54	0.00	0.05	0.27	0.23	0.00	0.00	-0.3*	0.43	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	•0.02	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	•0.00	0.00	0.00	0.00	0.00	•0.02
5	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	-0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	•0.03	0.00	-0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.29	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	-4.71	0.94	0.00	7.54	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-4.71	0.00
8	0.00	0.00	0.00	0.00	1.07	0.00	0.00	-1.07	1.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
10	0.00	0.00	0.00	0.00	0.00	0.00	4.01	0.00	0.00	8.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.01	0.00
11	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.81	1.43	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0,00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.00	-0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.00
13	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	•0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.07	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.04	0.00

Table A1.7 Marginal analysis for SIMPLE2A: sensitivity of x11 for changes in the system's set of equations

A1.7a Set of equations



A1.7b Marginal analysis

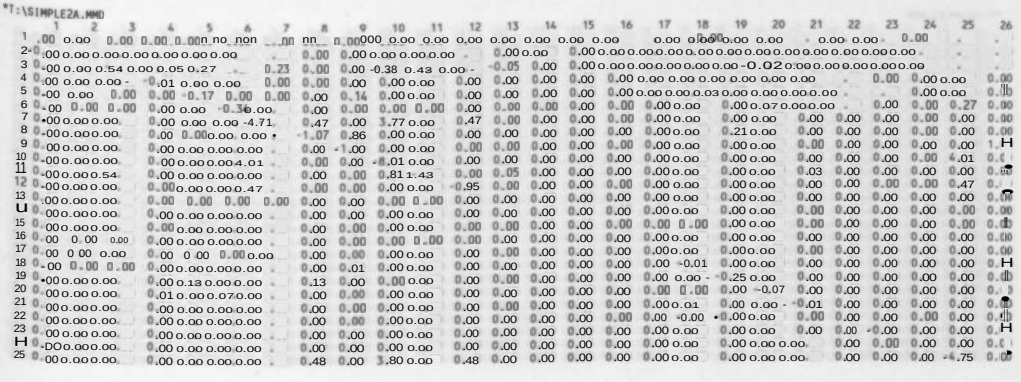


Table A1.8 Marginal analysis for SIMPLE3: sensitivity of x11 for changes in the system's set of equations

A1.8a Set of equations

SIMPLE3SFA

	KI	x2	x3	x4	xS	16	x7	x8	x9	XIO	x11	X|2	X|3	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	y
x1	1																									722
x2		1																								4
x3	-1	1	1																							0
x4				1																						**30**
x5					1																					62.5
x6						1																				361
»7							1																			312.5
x8								1																		62.5
x9					-1			-1	1										1							0
x10							-1	1		1		1													-1	0
xII			-1		1	1	1			-1	1		-1								-1					0
x12											1															**62.5**
x13		-1									-1	1										-1				0
x14													1													143
X15														1												143
x16											-1			1	1	1										0
x17														-1			1									0
x18									-1									1								0
X19																			1							**25**
x20																				1						78
X21																					1					20
«22																						1				2
x23																		-1	-1	-1	1	1	1			0
X24																							-1	1		0
X25				-1		-1														1					1	0

A1.8b Marginal analysis

*T:\SIMPLE3.MMO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	-1.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.X	0.00	0.00	0.00	0.00	0.00
3	126	-0.01	•1.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
10	0.00	0.00	0.00	0.00	0.00	0.00	0.55	•0.11	0.00	O.M	0.00	-0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55
11	0.00	0.00	1.26	0.00	-0.11	-0.63	-0.55	0.00	0.00	O.M	1.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	-0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M	O.M
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
15	O.M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	O.M
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O.M
25	0.00	0.00	0.00	0.05	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.14	O.M	0.00	0.00	O.M	•0.55

Table A1.9 Marginal analysis for SIMPLE4: sensitivity of x11 for changes in the system's set of equations

A1.9a Set of equations

SIMPLE4.SFA

	x1	«2	«3	x4	IS	x6	«7	«8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	y
x1	1	-1	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
x2	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
«3	.	.	1	.	-1	-1	-1	.	.	1	-1	.	1	.	.	.	.	.	.	.	1	.	.	.	.	0
x4	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	30
x5	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	62.5
»6	.	.	.	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	-1	.	.	.	.	-1	0
x7	.	.	.	.	.	.	1	-1	.	-1	.	-1	.	.	.	.	.	.	.	.	.	.	.	.	1	0
»8	.	.	.	.	1	.	.	1	-1	.	.	.	.	.	.	.	.	.	-1	.	.	.	.	.	.	0
x9	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
x10	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	100
x11	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	500
x12	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	571
x13	.	-1	.	.	.	.	.	.	.	.	.	-1	1	.	.	.	.	.	.	.	.	-1	.	.	.	625
x14	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	0
x15	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	143
x16	.	.	.	.	.	.	.	.	.	.	-1	.	.	1	1	1	.	.	.	.	.	.	.	.	.	143
X17	.	.	.	.	.	.	.	.	.	.	.	.	.	-1	.	.	1	.	.	.	.	.	.	.	.	0
x18	.	.	.	.	.	.	.	.	-1	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	0
x19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	0
x20	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	25
X21	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	78
x22	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	20
x23	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-1	-1	-1	1	1	1	.	.	2
»24	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-1	1	.	0
x25	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	0
																										312.5

A1.9b Marginal analysis

*T:\SIMPLE4.MMO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	2*	25	26
1	0.00	0.B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.[ ]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	•1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
13	0.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.W	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.lb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.(X	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2*	0.00	0.H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX 2 EVALUATION OF THE CASE STUDY "CADMIUM IN THE EUROPEAN COMMUNITY"

1 Description and evaluation of the bookkeeping data, 1987

The overview of cadmium flows in the European Union for 1987 is presented herewith as the SFINX-general view file CDEUR55X.GVW. In this appendix, the underlying data are discussed. The following process clusters are defined and treated separately:

1. zinc production and use
2. cadmium production and use
3. phosphate production and use
4. iron & steel production and use
5. fossil fuels production and use
6. building & road construction
7. **food production & consumption**
8. **municipal waste treatment**
9. other waste treatment
10. sewage treatment
11. **economic stock**
12. environment.

The first seven clusters contain recovery, production, use and consumption. The next three are concerned with waste treatment. Economic stock is the "delay" node; durable applications flow into it and discarded durable applications out of it. Some emissions, especially those connected to the use of durable applications, also flow out of this node. The balance deficit for this node is the total of economic accumulation. Clusters 1 to 11 are economic. Cluster 12, the environment cluster, contains the environmental compartments. Emissions and transboundary pollution flow into this cluster and extraction and transboundary pollution flow out. Each of these clusters is treated in a separate section derived from the SFINX-file is the guiding principle; for each cluster the appropriate SFINX-nodes are mentioned. Nodes between brackets refer to SFINX-nodes acting as a source or sink for the cluster under observations. The flows are all named by their SFINX x-variable number.

Most of the data have been collected by student researchers and published in a student report: L. van Egmond (1990): Beleidsgerichte analyse van cadmiumstromen in economie en milieu van de Europese Gemeenschap (Policy oriented analysis of cadmium flows in the European Community). This report is frequently referred to in the following text.

CDEUR55X.GVW

INPUTS OF Zn refinery FROM:			
Zn-ore extraction	1189.1500	tab/form	x0
Zn-ore import	3866.8914	tab/form	x1
Zn-scrap import	6.0210	tab/form	x2
waste treatment (municipal)	8.3777	formula	x13
waste treatment (remaining)	62.0600	formula	x94
==== Total =====	5132.5001		
OUTPUTS OF Zn refinery TO:			
Zn-ore export	173.2538	tab/form	x3
Zn-applying industry	235.1493	formula	x4
Cd-applying industry	4108.8658	formula	x5
air	22.9491	formula	x6
industrial waste water reception	17.0898	formula	x7
landfill	575.1924	bal.item*	x8
===== Total =====	5132.5001		
INPUTS OF Zn-applying industry FROM:			
Zn refinery	235.1493	formula	x4
Zn import	340.4765	tab/form	x9
==== Total =====	575.6258		
OUTPUTS OF Zn-applying industry TO:			
Zn export	62.6240	tab/form	x10
Zn-scrap export	15.6516	tab/form	x11
economic stock	497.3502	bal.item*	x12
==== Total =====	575.6258		
INPUTS OF Cd-applying industry FROM:			
Zn refinery	4108.8658	formula	x5
Cd import	2321.0000	tab/form	x113
==== Total =====	6429.8658		
OUTPUTS OF Cd-applying industry TO:			
Cd export	323,.0000	tab/form	x114
Cd-battery industry	1447,.3272	formula	x115
Cd-pigment industry	2180,.1511	formula	x123
Cd-stabilizer industry	1203.0526	formula	x131
Cd-surface coating industry	934,.3505	formula	x139
Cd-alloy industry	213,.7403	formula	x144
Cd-various industry	128..2442	bal.item*	x149
==== Total =====	6429..8658		
INPUTS OF Cd-battery industry FROM:			
Cd-applying industry	1447.3272	formula	x115
==== Total =====	1447.3272		
OUTPUTS OF Cd-battery industry TO:			
air	11.3760	formula	x117
industrial waste water reception	3.0973	formula	x118
landfill	34.0122	bal.item*	x119
Cd-battery consumption	1398.8417	formula	x120
==== Total =====	1447.3272		

INPUTS OF Cd-pigment industry FROM:			
Cd-applying industry	2180.1511	formula	x123
==== Total =====	2180.1511		
OUTPUTS OF Cd-pigment industry TO:			
industrial waste water reception	**20.9731**	**formula**	**Xl25**
landfill	51.1899	bal.item*x126	
Cd-pigment consumption	**2107.9881**	**formula**	**xl27**
==== Total =====	2180.1511		
INPUTS OF Cd-stabilizer industry FROM:			
Cd-applying industry	1203.0526	formula	xl31
==== Total =====	1203.0526		
OUTPUTS OF Cd-stabilizer industry TO:			
Cd-stabilizer consumption	1172.9762	formula	xl33
industrial waste water reception	0.9985	formula	xl37
landfill	**29.0778**	bal.item*x138	
==== Total =====	**1203.0526**		
INPUTS OF Cd-surface coating industry FROM:			
Cd-applying industry	934.3505	formula	xl39
==== Total =====	**934.3505**		
OUTPUTS OF Cd-surface coating industry TO:			
industrial waste water reception	19.7148	formula	xl40
landfill	**86.2405**	bal.item*x141	
Cd-surface coating consumption	828.3951	formula	x142
==== Total =====	934.3505		
INPUTS OF Cd-alloy industry FROM:			
Cd-applying industry	213.7403	formula	xl44
==== Total =====	213.7403		
OUTPUTS OF Cd-alloy industry TO:			
air	0.8037	formula	xl45
landfill	5.0314	bal.item*x146	
Cd-alloy consumption	207.9052	formula	xl47
==== Total =====	213.7403		
INPUTS OF Cd-various industry FROM:			
Cd-applying industry	128.2442	bal.item	x149
==== Total =====	128.2442		
OUTPUTS OF Cd-various industry TO:			
landfill	3.0522	bal.item*x151	
Cd-various consumption	125.1920	formula	xl52
==== Total =====	**128.2442**		
INPUTS OF Cd-battery consumption FROM:			
Cd-battery industry	1398.8417	formula	xl20
Cd-battery import	2160.1000	tab/form	xl21
==== Total =====	3558.9417		
OUTPUTS OF Cd-battery consumption TO:			
Cd-battery export	313.1000	tab/form	xll6
economic stock	3245.8417	bal.item*x122	
==== Total =====	3558.9417		

INPUTS OF Cd-pigment consumption FROM:			
Cd-pigment industry	2107.9881	formula	xl27
Cd-pigment import	16.1870	tab/form	xl28
==== Total =====	2124.1751		
OUTPUTS OF Cd-pigment consumption TO:			
Cd-pigment export	**467.8905**	**tab/form**	**xl24**
economic stock	**1496.0390**	**bal.item*x129**	
waste treatment (municipal)	**160.2455**	**formula**	**xl30**
==== Total =====	**2124.1751**		
INPUTS OF Cd-stabilizer consumption FROM:			
Cd-stabilizer industry	1172.9762	formula	xl33
Cd-stabilizer import	211.8374	tab/form	xl34
==== Total =====	1384.8136		
OUTPUTS OF Cd-stabilizer consumption TO:			
Cd-stabilizer export	420.4808	tab/form	xl32
economic stock	804.0607	bal.item*x135	
waste treatment (municipal)	**160.2721**	formula	xl36
==== Total =====	**1384.8136**		
INPUTS OF Cd-surface coating consumption FROM:			
Cd-surface coating industry	828.3951	formula	xl42
==== Total =====	828.3951		
OUTPUTS OF Cd-surface coating consumption TO:			
economic stock	**828.3951**	bal.item*x143	
==== Total =====	**828.3951**		
INPUTS OF Cd-alloy consumption FROM:			
Cd-alloy industry	207.9052	formula	xl47
==== Total =====	207.9052		
OUTPUTS OF Cd-alloy consumption TO:			
economic stock	207.9052	bal.item*x148	
==== Total =====	207.9052		
INPUTS OF Cd-various consumption FROM:			
Cd-various industry	125.1920	formula	xl52
Cd-various import	9.0000	tab/form	xl53
==== Total =====	134.1920		
OUTPUTS OF Cd-various consumption TO:			
Cd-various export	132.0000	tab/form	x150
economic stock	2.1920	bal.item*x154	
==== Total =====	134.1920		
INPUTS OF P-refinery FROM:			
P-rock import	510.7712	tab/form	x24
==== Total =====	510.7712		
OUTPUTS OF P-refinery TO:			
building industry	3.9993	formula	x25
agricultural soil	3.9993	formula	x26
waste gypsum disposal at sea	24.9767	formula	x27
industrial waste water reception	74.9812	formula	x28
landfill	96.3519	bal.item*x29	
P-applying industry	306.4627	formula	x92
==== Total =====	510.7712		

INPUTS OF P-applying industry FROM:			
P-acid (and other products) import	33.9700	tab/form	x30
P-fertilizer import	256.2295	tab/form	x31
P-refinery	306.4627	formula	x92
==== **Total** =====	**596.6622**		
OUTPUTS OF **P-applying industry** TO:			
P-acid (and other products) export	84.9600	tab/form	x32
P-fertilizer export	**33.5635**	tab/form	x33
waste treatment (municipal)	109.4014	bal.item*x34	
agricultural soil	333.5342	formula	x35
fodder industry	35.2031	formula	x36
==== Total =====	596.6622		
INPUTS OF Fe refinery FROM:			
Fe-ore extraction	2.4852	tab/form	x37
Fe-ore import	17.7760	tab/form	x38
waste treatment (remaining)	349.1600	formula	x93
waste treatment (municipal)	42.8192	formula	x95
==== Total =====	412.2404		
OUTPUTS OF Fe refinery TO:			
air	18.1386	formula	x39
industrial waste water reception	21.0243	formula	x40
landfill	255.1768	bal.item*x41	
Fe-applying industry	32.1547	formula	x42
cement industry	85.7460	formula	x44
==== Total =====	412.2404		
INPUTS OF Fe-applying industry FROM:			
Fe refinery	32.1547	formula	x42
==== Total =====	32.1547		
OUTPUTS OF Fe-applying industry TO:			
economic stock	32.1547	bal.item*x43	
==== Total =====	32.1547		
INPUTS OF cement industry FROM:			
Fe refinery	85.7460	formula	x44
energy production	9.9292	formula	x54
marl extraction	345.0000	formula	x73
==== Total =====	440.6752		
OUTPUTS OF cement industry TO:			
air	7.0508	formula	x74
landfill	261.7611	bal.item*x75	
building industry	171.8633	formula	x76
==== Total =====	440.6752		
INPUTS OF fossil fuels refinery FROM:			
fossil fuels extraction	54.6000	tab/form	x45
fossil fuels import	75.9613	tab/form	x46
==== Total =====	130.5614		
OUTPUTS OF fossil fuels refinery TO:			
fossil fuels export	17.7667	tab/form	x47
petroleum-applying industry	36.4163	bal.item*x48	
energy production	76.3784	formula	x51
==== Total =====	130.5614		

INPUTS OF energy production FROM:				
	fossil fuels refinery	76.3784	formula	x51
	==== Total =====	76.3784		
OUTPUTS OF energy production TO:				
	air	35.1341	formula	x52
	landfill	31.3151	bal.item	*x53
	cement industry	9.9292	formula	x54
	==== Total =====	76.3784		
INPUTS OF petroleum-applying industry FROM:				
	fossil fuels refinery	36.4163	bal.item	x48
	==== Total =====	36.4163		
OUTPUTS OF petroleum-applying industry TO:				
	economic stock	25.4914	formula	x49
	waste treatment (municipal)	10.9249	bal.item	*x50
	===== Total =====	36.4163		
INPUTS OF building industry FROM:				
	P-refinery	3.9993	formula	x25
	cement industry	171.8633	formula	x76
	==== Total =====	175.8627		
OUTPUTS OF building industry TO:				
	economic stock	175.8627	bal.item	*x77
	==== Total =====	175.8627		
INPUTS OF road construction FROM:				
	waste treatment (municipal)	66.0905	formula	x78
	==== Total =====	66.0905		
OUTPUTS OF road construction TO:				
	economic stock	66.0905	bal.item	*x79
	==== Total =====	66.0905		
INPUTS OF **agricultural soil** FROM:				
	P-refinery	3.9993	formula	x26
	P-applying industry	333.5342	formula	x35
	fertilizer (not P) import	42.9990	tab/form	x55
	sewage water treatment	21.6094	formula	x56
	waste treatment (municipal)	27.9255	formula	x57
	stock raising	117.0347	bal.item	x68
	agricultural soil	57.3470	formula	x72
	air	85.7033	formula	x96
	==== Total =====	690.1525		
OUTPUTS OF agricultural soil TO:				
	crop/grass export	2.0048	formula	x58
	air	35.1542	formula	x59
	surface water	4.6624	formula	x60
	ground water	93.2472	formula	x61
	food industry	9.0217	formula	x62
	stock raising	66.2055	formula	x66
	fodder industry	16.0851	formula	x69
	agricultural soil	57.3470	formula	x72
	environment	406.4247	bal.item	*x159
	==== Total =====	690.1525		

INPUTS OF food industry FROM:			
agricultural soil	9.0217	formula	x62
==== Total =====	9.0217		
OUTPUTS OF food industry TO:			
food consumption	9.0217	bal.item*x63	
===== Total =====	9.0217		
INPUTS OF fodder industry FROM:			
P-applying industry	35.2031	formula	x36
agricultural soil	16.0851	formula	x69
fodder import	2.5419	tab/form	x70
===== Total =====	53.8301		
OUTPUTS OF fodder industry TO:			
stock raising	53.8301	bal.item*x71	
==== Total =====	53.8301		
INPUTS OF **stock raising** FROM:			
agricultural soil	66.2055	formula	x66
fodder industry	53.8301	bal. item	x71
==== Total =====	120.0356		
OUTPUTS OF stock raising TO:			
food consumption	3.0009	formula	x67
agricultural soil	117.0347	bal.item*x68	
==== Total =====	120.0356		
INPUTS OF food consumption FROM:			
food industry	9.0217	bal. item	x63
stock raising	3.0009	formula	x67
==== Total =====	12.0226		
OUTPUTS OF food consumption TO:			
waste treatment (municipal)	4.0075	formula	x64
sewage water treatment	8.0150	bal.item*x65	
==== Total =====	12.0226		
INPUTS OF economic stock FROM:			
Zn-applying industry	497.3502	bal. item	xl2
Fe-applying industry	32.1547	bal. item	x43
petroleum-applying industry	25.4914	formula	x49
building industry	175.8627	bal. item	x77
road construction	66.0905	bal. item	x79
Cd-battery consumption	3245.8417	bal. item	xl22
Cd-pigment consumption	1496.0390	bal. item	xl29
Cd-stabilizer consumption	804.0607	bal. item	xl35
Cd-surface coating consumption	828.3951	bal. item	xl43
Cd-alloy consumption	207.9052	bal. item	xl48
Cd-various consumption	2.1920	bal. item	xl54
==== Total =====	7381.3832		
OUTPUTS OF economic stock TO:			
waste treatment (municipal)	486.0000	formula	x8l
waste treatment (remaining)	580.0000	formula	x82
economy	6309.3832	bal.item*x171	
non-agricultural soil	6.0000	formula	xl72
==== Total =====	7381.3832		

INPUTS OF waste treatment (municipal) FROM:			
P-applying industry	109.4014	bal. item	x34
petroleum-applying industry	10.9249	bal. item	x50
food consumption	4.0075	formula	x64
economic stock	486.0000	formula	x81
Cd-pigment consumption	160.2455	formula	xl30
Cd-stabilizer consumption	160.2721	formula	xl36
==== Total =====	930.8515		
OUTPUTS OF waste treatment (municipal) TO:			
Zn refinery	8.3777	formula	xl3
agricultural soil	27.9255	formula	x57
road construction	66.0905	formula	x78
air	20.4787	formula	x83
landfill	765.1599	bal.item*x84	
Fe refinery	42.8192	formula	x95
==== Total =====	930.8515		
INPUTS OF waste treatment (remaining) FROM:			
economic stock	580.0000	formula	x82
sediment	65.7628	formula	x97
==== Total =====	645.7628		
OUTPUTS OF waste treatment (remaining) TO:			
sludge disposal at sea	21.7017	formula	x85
strategic storage	5.9187	formula	x86
landfill	206.9224	bal.item*x87	
Fe refinery	349.1600	formula	x93
Zn refinery	62.0600	formula	x94
==== Total =====	645.7628		
INPUTS OF industrial waste water reception FROM:			
Zn refinery	17.0898	formula	x7
P-refinery	74.9812	formula	x28
Fe refinery	21.0243	formula	x40
Cd-battery industry	3.0973	formula	xll8
Cd-pigment industry	20.9731	formula	xl25
Cd-stabilizer industry	0.9985	formula	xl37
Cd-surface coating industry	19.7148	formula	xl40
==== Total =====	157.8789		
OUTPUTS OF industrial waste water reception TO:			
sewage water treatment	100.0321	formula	x98
surface water	57.8468	bal.item*x168	
==== Total =====	157.8789		
INPUTS OF sewage water treatment FROM:			
food consumption	8.0150	bal. item	x65
industrial waste water reception	100.0321	formula	x98
==== Total =====	108.0471		
OUTPUTS OF sewage water treatment TO:			
agricultural soil	21.6094	formula	x56
sewage sludge disposal at sea	3.2414	formula	x88
air	2.0529	formula	x89
surface water	54.0235	formula	x90
landfill	27.1198	bal.item*x91	
==== Total =====	108.0471		

INPUTS OF air FROM:			
Zn refinery	22.9491	formula	x6
Fe refinery	18.1386	formula	x39
energy production	35.1341	formula	x52
agricultural soil	35.1542	formula	x59
cement industry	7.0508	formula	x74
waste treatment (municipal)	20.4787	formula	x83
sewage water treatment	2.0529	formula	x89
transboundary inflow air	20.0000	formula	xl06
Cd-battery industry	11.3760	formula	xll7
Cd-alloy industry	0.8037	formula	xl45
==== Total =====	173.1380		
OUTPUTS OF air TO:			
agricultural soil	85.7033	formula	x96
surface water	1.7314	bal.item*x107	
non-agricultural soil	85.7033	formula	xl60
==== Total =====	173.1380		
INPUTS OF surface water FROM:			
agricultural soil	4.6624	formula	x60
sewage water treatment	54.0235	formula	x90
air	1.7314	bal.item	xl07
landfill	24.2760	formula	xl08
transboundary inflow surface water	17.0000	formula	x111
non-agricultural soil	0.8570	formula	xl62
industrial waste water reception	57.8468	bal.item	xl68
==== Total =====	160.3972		
OUTPUTS OF surface water TO:			
sediment	131.5257	formula	xl09
transboundary outflow surface water	28.8715	bal.item*x110	
==== Total =====	160.3972		
INPUTS OF ground water FROM:			
agricultural soil	93.2472	formula	x61
non-agricultural soil	17.1407	formula	xl63
==== Total =====	110.3878		
OUTPUTS OF ground water TO:			
environment	110.3878	bal.item*x156	
==== Total =====	110.3878		
INPUTS OF sediment FROM:			
surface water	131.5257	formula	xl09
==== Total =====	131.5257		
OUTPUTS OF sediment TO:			
waste treatment (remaining)	65.7628	formula	x97
environment	65.7628	bal.item*x157	
===== Total =====	131.5257		

INPUTS OF non-agricultural soil FROM:			
air	85.7033	formula	X160
economic stock	6.0000	formula	xl72
==== Total =====	91.7033		
OUTPUTS OF non-agricultural soil TO:			
surface water	0.8570	formula	xl62
ground water	17.1407	formula	x163
environment	73.7056	bal.item*x165	
==== Total =====	91.7033		
INPUTS OF landfill FROM:			
Zn refinery	575.1924	bal. item	x8
P-refinery	96.3519	bal.item	x29
Fe refinery	255.1768	bal.item	X41
energy production	31.3151	bal.item	x53
cement industry	261.7611	bal.item	x75
waste treatment (municipal)	765.1599	bal. item	x84
waste treatment (remaining)	206.9224	bal.item	X87
sewage water treatment	27.1198	bal.item	x91
Cd-battery industry	34.0122	bal.item	X119
Cd-pigment industry	51.1899	bal.item	x126
Cd-stabilizer industry	29.0778	bal.item	X138
Cd-surface coating industry	86.2405	bal.item	X141
Cd-alloy industry	5.0314	bal.item	x146
Cd-various industry	3.0522	bal.item	X151
==== Total =====	2427.6036		
OUTPUTS OF landfill TO:			
surface water	24.2760	formula	x108
environment	2403.3275	bal.item*x158	
==== Total =====	2427.6036		

1.1 Zinc production and use

nodes
zinc refinery
zinc application industry
(other waste treatment)
(cadmium industry)
(economic stock)
(environmental nodes)

flows
x1 import Zn ore
xO recovery Zn ore
x3 export Zn ore
* trade and production statistics for amounts of material, presumably quite reliable (Eurostat, 1990a, Eurostat, 1990c, Van Egmond, 1990)
* various sources for content of Cd (as summarized in Van Egmond, 1990), which might contain inaccuracies.

x9 import refined Zn
x10 export refined Zn
* trade statistics for the amounts of material (Eurostat, 1990c, Eurostat, 1991)
* various sources for amount of Cd - which could be inaccurate and has decreased significantly recently (as summarized in Van Egmond, 1990).

x4 delivery primary and secondary zinc to applications industry
xl2 delivery Zn applications to users
* amount of material: balancing item of zinc industry in terms of total materials
* assumption of Cd content of 1 mg/kg, which could be inaccurate. A distinction has been made between thermic and electrolytic zinc production, and the production of secondary zinc. Zinc from thermic production is estimated to contain 95 mg/kg Cd. The assumption is that this Cd is extracted and sold, and that the remaining Cd content is 1 mg/kg. Electrolytically produced zinc contains 1 mg/kg cadmium (Van Egmond, 1990).

x2 import Zn scrap
x11 export Zn scrap
* trade and production statistics for amount of material (Eurostat 1990c, Eurostat 1991)
* content of Cd could be inaccurate (see x12). Is not independent of inaccuracies as above.

scrap recycling
* the division between Zn and Fe scrap was made for the total amount of scrap (municipal and other), and was determined by the Fe balance, where 392 tonnes of Cd were needed to balance the Fe production node. The remainder, 70 tonnes of Cd, therefore was assumed to be Cd in zinc scrap. No data were found to support this, but it does not appear unreasonable.

scrap from municipal waste
* see Van Egmond, appendix 3.3 table 3.12: estimated by multiplying the amount of municipal waste (OECD, 1991) by the average Cd content (10 mg/kg, ERL (1989)). Recycled scrap, according to Van Egmond (1990), amounts in terms of Cd to 25% of the incinerated waste.

scrap from other waste

* No information is available. The total amount was estimated at 411 tonnes of Cd as a balancing item of the "other waste" balance. This is probably due to used cars and demolition waste and certainly can be explained that way, but there are no data to confirm this.

x13 recycling Zn scrap, municipal waste
x94 recycling Zn scrap, other waste
* estimated by extrapolating the division Zn/Fe (70/392, see above) to the two scrap categories.

x5 delivery of Cd to Cd applications industry
this flow contains two separate deliveries: Cd extracted from Zn ore, and Cd in Cu/Co sludge.
* extraction of cadmium from Zn ore: amount of material: productions statistics (Eurostat, 1990a); Cd content: own assumption 99.95%.
* Cu/Co sludge: the amount of Cd is unknown. Together with the jarosite emission this flow is estimated as the balancing item of the zinc ore refinery node. The distribution over the two items is assumed to be 2:1 (Van der Voet et al., 1989).

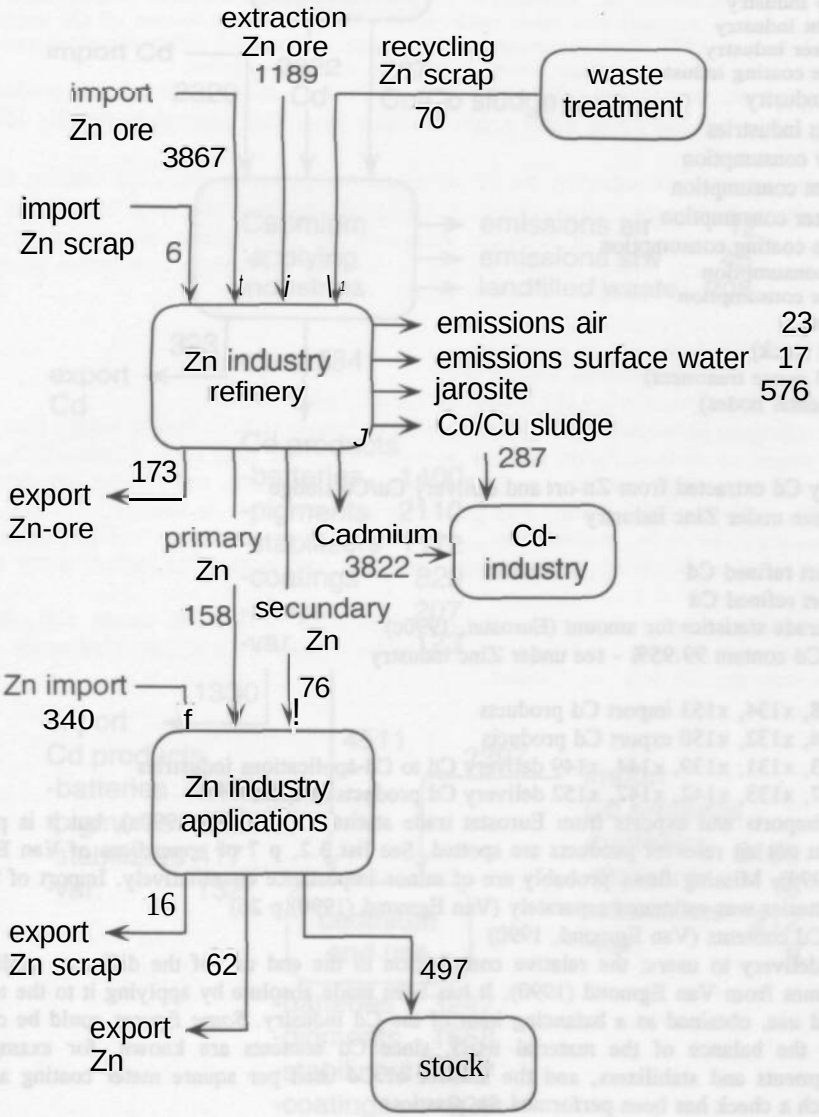
x6 emissions air
* source: ERL (1989).

x7 emissions surface water "industrial waste water reception"
* source: ERL (1989), part of this is not emitted directly but rather via sewage treatment. This is accounted for in the overview by connecting the industry with an "industrial waste water reception" node linked to the sewage treatment, and making the surface water emission take place from there.

x8 landfill jarosite
* see under x5 Cu/Co sludge.

No data are available on the emissions (probably mainly landfill) that go with the mining process itself.

Figure A2.1 Flow chart zinc production and use (tonnes Cd/year, 1987) = =



1.2 Cadmium production and use

nodes
cadmium industry
Cd battery industry
Cd pigment industry
Cd stabilizer industry
Cd surface coating industry
Cd alloy industry
Cd various industries
Cd battery consumption
Cd pigment consumption
Cd stabilizer consumption
Cd surface coating consumption
Cd alloy consumption
Cd various consumption
(zinc refinery)
(economic stock)
(municipal waste treatment)
(environmental nodes)

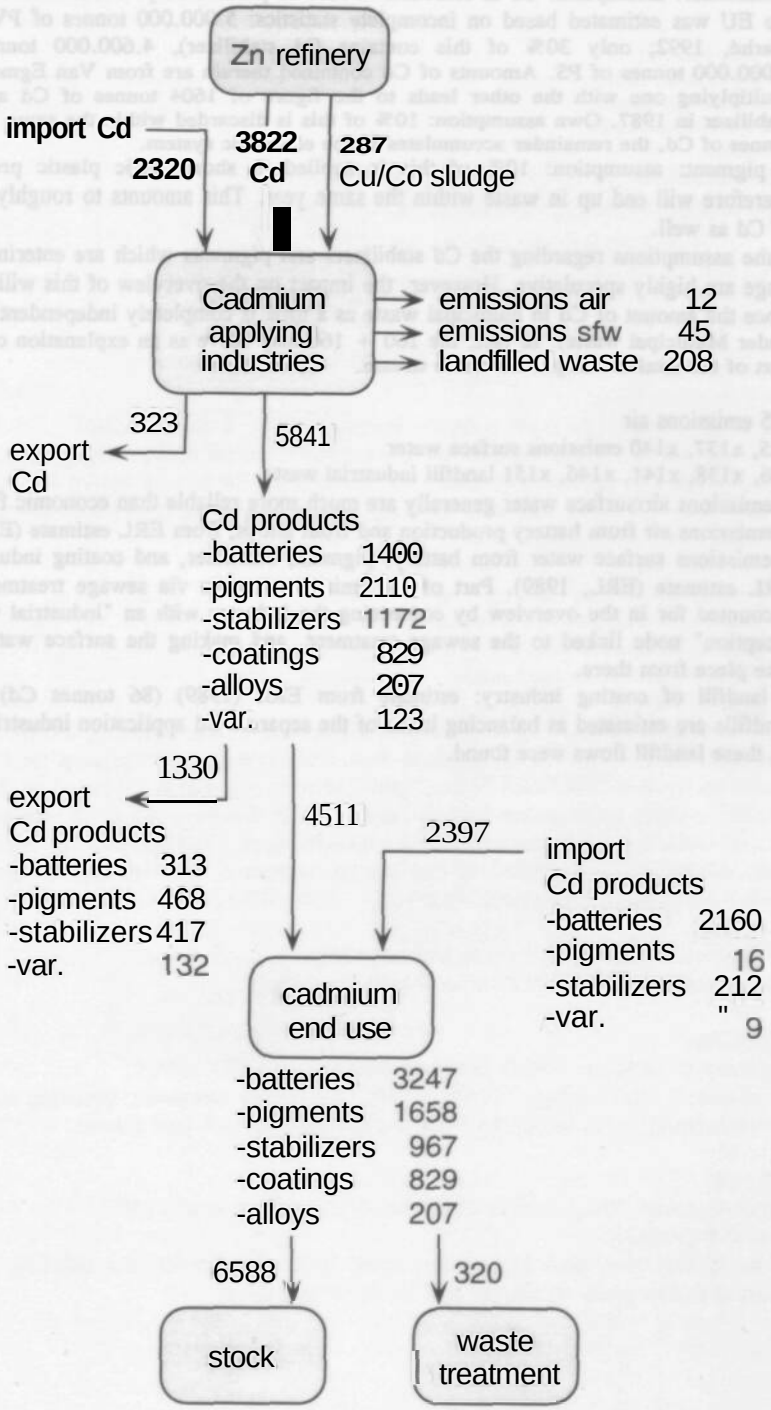
flows
x5 delivery Cd extracted from Zn-ore and delivery Cu/Co sludge
* see under Zinc industry

x113 import refined Cd
x114 export refined Cd
* trade statistics for amount (Eurostat, 1990c)
* Cd content 99.95% - see under Zinc industry

xl21, xl28, xl34, xl53 import Cd products
x116, xl24, x132, x150 export Cd products
xll5, xl23, xl31, xl39, xl44, xl49 delivery Cd to Cd-applications industries
xl20, xl27, xl33, xl42, xl47, xl52 delivery Cd products to users
* imports and exports from Eurostat trade statistics (Eurostat, 1990c), but it is possible that not all relevant products are spotted. See list 3.2, p 7 of appendices of Van Egmond (1990). Missing flows probably are of minor importance quantitatively. Import of built-in batteries was estimated separately (Van Egmond (1990) p 26)
* Cd contents (Van Egmond, 1990)
* delivery to users: the relative contribution in the end use of the different applications comes from Van Egmond (1990). It has been made absolute by applying it to the total Cd end use, obtained as a balancing item of the Cd industry. Some figures could be checked by the balance of the material itself, since Cd contents are known, for example, of pigments and stabilizers, and the amount of Cd used per square meter coating as well. Such a check has been performed for plastics.
* by balancing imports, exports and end use of every application, the production levels for the separate applications were derived as balancing items.

xl22, xl29, xl35, xl43, xl48, xl54 Cd products added to economic stock
* = end use minus discarding of short-lived products (< 1 year)

Figure A2.2 Flow chart cadmium industry (tonnes Cd/year, 1987)



xl30, xl36 Cd products being discarded to waste treatment

* stabilizer: assumption: Cd as stabilizer is used in plastics only. Production of plastics in the EU was estimated based on incomplete statistics: 5.000.000 tonnes of PVC (Bhairo-Marhé, 1992; only 30% of this contains Cd stabilizer), 4.600.000 tonnes of PE, 2.000.000 tonnes of PS. Amounts of Cd contained therein are from Van Egmond (1990). Multiplying one with the other leads to the figure of 1604 tonnes of Cd applied as a stabilizer in 1987. Own assumption: 10% of this is discarded within the same year = 160 tonnes of Cd, the remainder accumulates in the economic system.
* pigment: assumption: 10% of this is applied in short cyclic plastic products, and therefore will end up in waste within the same year. This amounts to roughly 160 tonnes of Cd as well.
* the assumptions regarding the Cd stabilizers and pigments which are entering the waste stage are highly speculative. However, the impact on the overview of this will be limited, since the amount of Cd in municipal waste as a total is completely independent of this (see under Municipal waste). In fact, the 160 + 160 may serve as an explanation concerning a part of the total municipal Cd waste stream.

x117, xl45 emissions air

x118, xl25, xl37, x140 emissions surface water

xll9, xl26, xl38, xl41, xl46, xl51 landfill industrial waste

* emissions air/surface water generally are much more reliable than economic flow data
* emissions air from battery production and from alloys, from ERL estimate (ERL, 1989).
* emissions surface water from battery, pigment, stabilizer, and coating industries, from ERL estimate (ERL, 1989). Part of the emissions occurs via sewage treatment. This is accounted for in the overview by connecting the industry with an "industrial waste water reception" node linked to the sewage treatment, and making the surface water emission take place from there.
* landfill of coating industry: estimate from ERL (1989) (86 tonnes Cd). All other landfills are estimated as balancing items of the separate Cd application industries. No data on these landfill flows were found.

1.3 Phosphate production and use

nodes
phosphate rock refinery
phosphate application industry
use of phosphate applications
(municipal waste treatment)
(building sector)
(crop/grass production)
(environmental nodes)

flows
x24 import P-rock
x30 import P-acid
x32 export P-acid
x31 import P-fertilizer
x33 export P-fertilizer
* amount of materials: trade statistics (Eurostat, 1990c; Eurostat, 1991)
* Cd-content in P-rock: margins are given from 15 to 80 mg/kg, 35 mg/kg is used. In P-acid, 30 mg/kg was taken if meant for fodder additive and 80 mg/kg for fertilizer. For detergent-P, 53 mg/kg was used (coming from 2 mg/kg P_2O_5). Various sources, see Van Egmond (1990), appendices p 3.

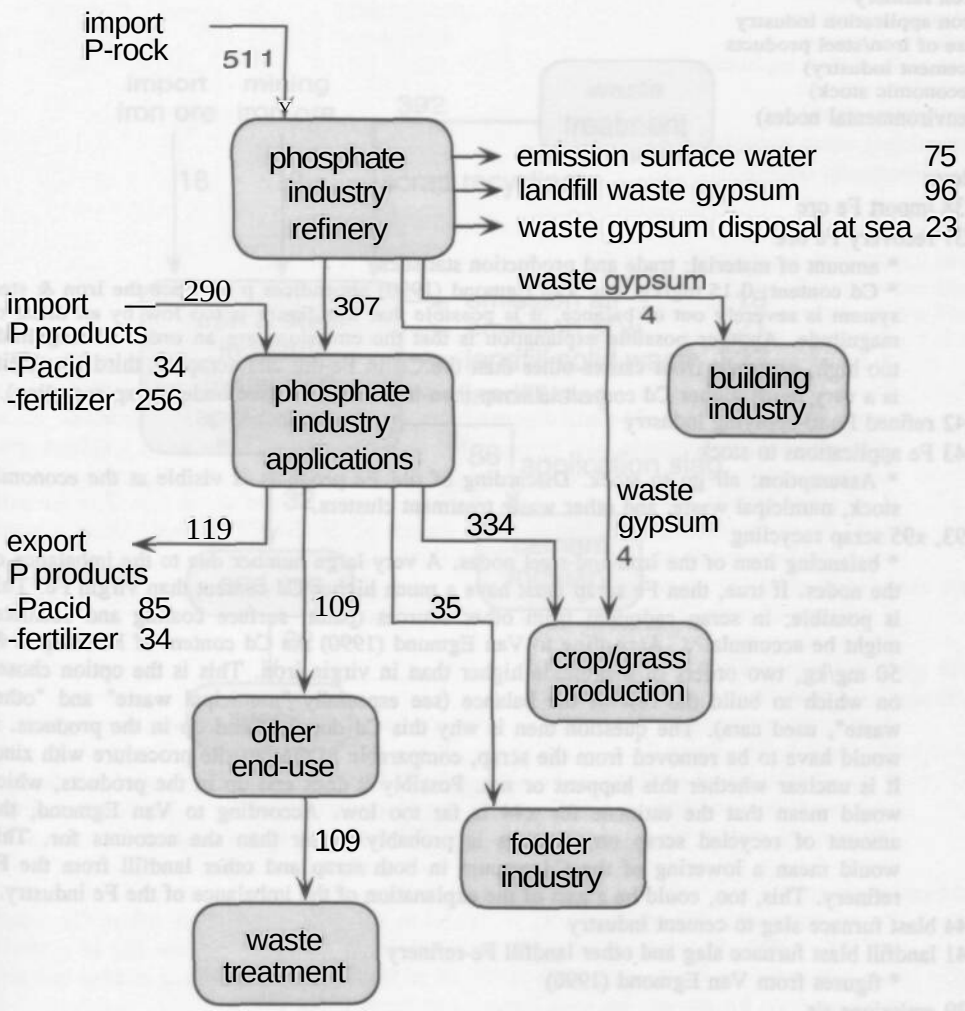
x25 waste gypsum to building industry
x26 waste gypsum to crop/grass production
x27 waste gypsum dumped in seas
x28 waste gypsum emission surface water
x29 waste gypsum landfill
* Cd ending up in waste gypsum: 60% of Cd in P-rock (Van Egmond, 1990).
* relative destination of waste gypsum: from UN Economic Commission for Europe, with additional distinction between "direct" and "indirect" disposal at sea based on SRI (1985).
* waste gypsum emissions to surface water: part of this takes place via sewage treatment. This is accounted for in the overview by connecting the industry with an "industrial waste water reception" node linked to the sewage treatment, and making the surface water emission take place from there.

x92 flow from P-rock refinery to P-applications industry
* estimated as balancing item of the P-refinery node

x35 P-fertilizer use
* amount of fertilizer: OECD Environmental Data (OECD, 1991)
* Cd-content (75 mg/kg): CCRX (1989). Variability unknown, probably considerable, probably equal to the variability in the Cd content in P-rock (see above).

x36 P-fodder use
* upscaling from data for the Netherlands (Van der Voet et al., 1989)
x34 disposal of P-products
* use is unknown, estimated as balancing item of P-applications industry. disposal is assumed to take place within the year for the total number.

Figure A2.3 Flow chart phosphate industry (tonnes/year Cd, 1987)



1.4 Iron & steel production and use

nodes
iron refinery
iron application industry
use of iron/steel products
(cement industry)
(economic stock)
(environmental nodes)

flows
x38 import Fe ore
x37 recovery Fe ore
* amount of material: trade and production statistics
* Cd content: 0.15 mg/kg, see Van Egmond (1990) appendices p 1. Since the Iron & steel system is severely out of balance, it is possible that this figure is too low by an order of magnitude. Another possible explanation is that the emissions are an order of magnitude too high, or result from causes other than the Cd in Fe-ore and scrap. A third possibility is a very much higher Cd content in scrap than in primary Fe (see under scrap recycling).

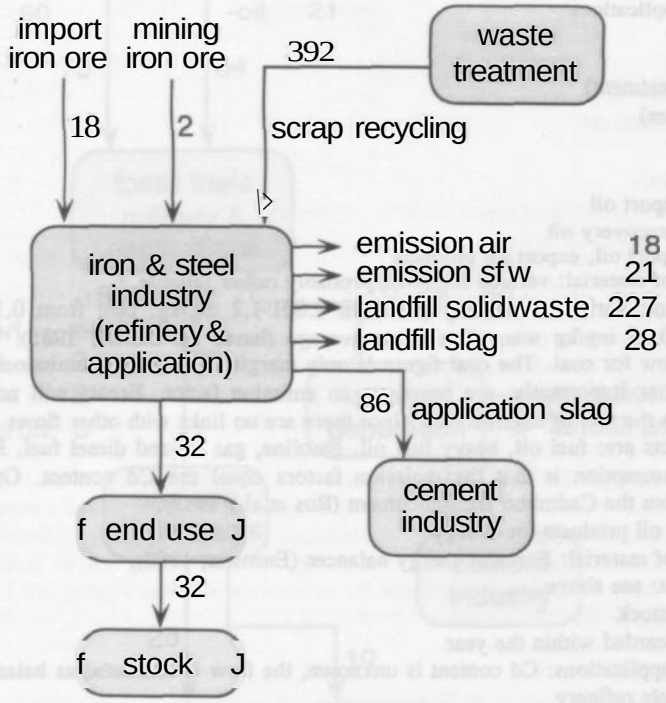
x42 refined Fe to applying industry
x43 Fe applications to stock
* Assumption: all go to stock. Discarding of old Fe products is visible at the economic stock, municipal waste, and other waste treatment clusters.

x93, x95 scrap recycling
* balancing item of the iron-and-steel nodes. A very large number due to the imbalance of the nodes. If true, then Fe scrap must have a much higher Cd content than virgin Fe. This is possible; in scrap cadmium from other sources (paint, surface coating and suchlike) might be accumulated. According to Van Egmond (1990) the Cd content of Fe scrap is 8-50 mg/kg, two orders of magnitude higher than in virgin iron. This is the option chosen on which to build the rest of the balance (see especially "municipal waste" and "other waste", used cars). The question then is why this Cd does not end up in the products. It would have to be removed from the scrap, comparable to the jarosite procedure with zinc. It is unclear whether this happens or not. Possibly it does end up in the products, which would mean that the estimate for x44 is far too low. According to Van Egmond, the amount of recycled scrap on premises is probably higher than she accounts for. This would mean a lowering of the Cd amount in both scrap and other landfill from the Fe refinery. This, too, could be a part of the explanation of the imbalance of the Fe industry.

x44 blast furnace slag to cement industry
x41 landfill blast furnace slag and other landfill Fe-refinery
* figures from Van Egmond (1990)

x39 emissions air
x40 emissions surface water
* the emissions from fossil fuels are excluded here (so this cannot be the cause of the high emissions)
* emissions to air and surface water: ERL (1989).
* emissions to surface water: part of these occur via sewage treatment. This is accounted for in the overview by connecting the industry with an "industrial waste water reception" node linked to the sewage treatment, and making the surface water emission take place from there.
* other landfill is mainly blast furnace slag. As stated before, part of this probably is recycled. See Van Egmond (1990) appendix 3.3.

Figure A2.4 Flow chart iron & steel industry (tonnes Cd/year, 1987)



1.5 Fossil fuels production and use

nodes
fossil fuel refinery
energy generation
cokes production
use of fossil fuel applications
(cement industry)
(economic stock)
(municipal waste treatment)
(environmental nodes)

flows
x46 import coal, import oil
x45 recovery coal, recovery oil
x47 export coal, export oil, export oil products
* amounts of material: various statistics, probably rather reliable.
* Cd content: varies enormously (oil from 0.001-1.2 mg/kg, coal from 0.1-65 mg/kg). For both, 0.15 mg/kg was taken as an average (based on CCRX, 1985). This may be somewhat low for coal. The coal figure is only marginally checked: emissions into air are low and more importantly, are based on an emission factor. Errors will not have great influence on the rest of the overview since there are no links with other flows.
* oil products are: fuel oil, heavy fuel oil, gasoline, gas oil and diesel fuel. For the latter two, the assumption is that the emission factors equal the Cd content. Other contents originate from the Cadmium Basisdocument (Ros et al., 1989).

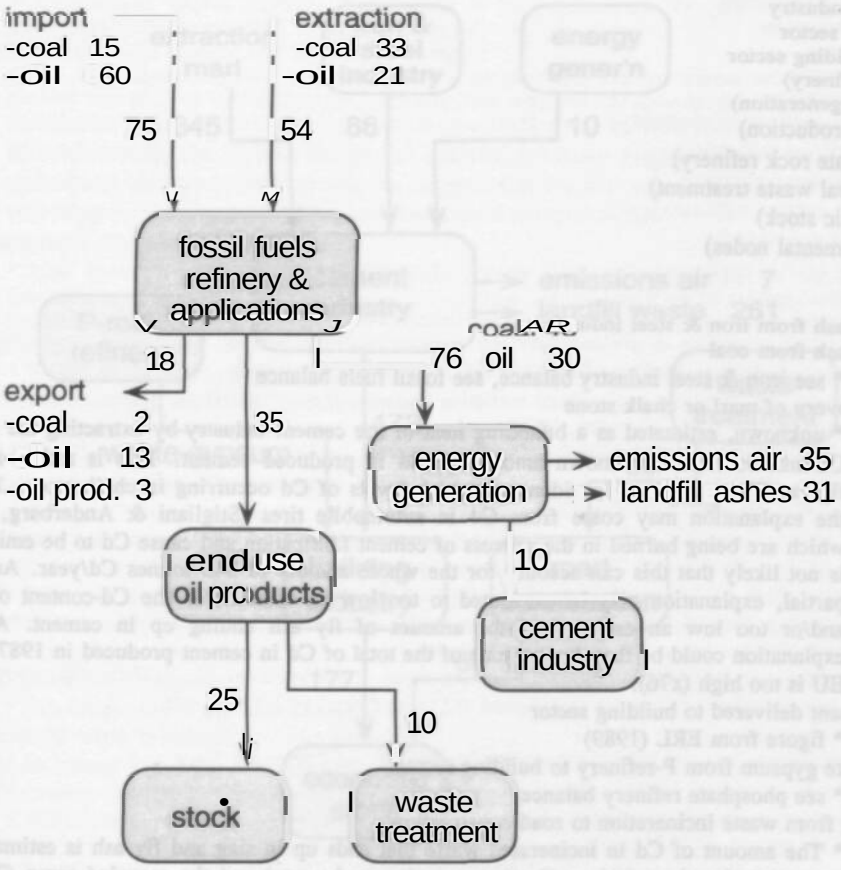
x51 use of coal and oil products for energy
* amounts of material: Eurostat energy balances (Eurostat, 1988).
* Cd-content: see above.

x49 applications to stock
x50 applications discarded within the year
* other oil applications: Cd content is unknown, the flow is estimated as balancing item of the fossil fuels refinery
* the distribution of applications over "stock" and "discarded within the year" is unknown, own assumption of 70% vs. 30% since it concerns plastics mostly in applications with a life-span of over a year. See remark under Cd-products being discarded to waste treatment.

x51 emissions air
* coal for energy: 2% of Cd content is emitted to air; cokes production: 3% of Cd content (CCRX, 1985). These are factors for the Netherlands scaled up for the EU as a whole. For other coal the (own) assumption is that all of the Cd contained in it is emitted into air.
* oil products for energy: emission factors (see above under x47)

x53 landfill ash
x54 fly ash to cement industry
* Of the Cd contained in coal, 98% of the coal used for energy and 97% of the coal used for cokes production ends up in ash. These fractions are the counterparts of the emissions into the atmosphere (see under x51)
* distribution over landfill/cement industry: two thirds/one third, own assumption based on 58.8% to cement industry in the Netherlands and the idea that this will be much lower for the EU as a whole. This is a very uncertain assumption, also in the light of the building & road construction balance.

Figure A2.5 Flow chart fossil fuels



1.6 Building & road construction

nodes
cement industry
building sector
road building sector
(iron refinery)
(energy generation)
(cokes production)
(phosphate rock refinery)
(municipal waste treatment)
(economic stock)
(environmental nodes)

flows
x44 fly ash from iron & steel industry
x54 fly ash from coal

* see iron & steel industry balance, see fossil fuels balance

x73 recovery of marl or chalk stone

* unknown, estimated as a balancing item of the cement industry by extracting the known Cd-inflows from the known amount of Cd in produced cement. This is rather a large figure. There is no real evidence for high levels of Cd occurring in chalk stone, Part of the explanation may come from Cd in automobile tires (Stigliani & Anderberg, 1992) which are being burned in the process of cement fabrication and cause Cd to be emitted. It is not likely that this can account for the whole amount of 345 tonnes Cd/year. Another, partial, explanation may be attributed to too low an estimate of the Cd-content of coal, and/or too low an estimate of the amount of fly ash ending up in cement. A third explanation could be that the estimate of the total of Cd in cement produced in 1987 in the EU is too high (x76).

x76 cement delivered to building sector

* figure from ERL (1989)

x25 waste gypsum from P-refinery to building sector

* see phosphate refinery balance

x78 slag from waste incineration to road construction

* The amount of Cd in incinerated waste that ends up in slag and fly ash is estimated by extracting the air emissions (1 g/tonne incinerated waste) and the recycled scrap (25% of the Cd in incinerated waste) from the total amount of incinerated waste. Of the Cd ending up in slag and ash, the (rough) assumption (by Van Egmond) is that 50% of this is landfilled and 50% is used in road construction.

x77, x79 building/road construction materials to stock

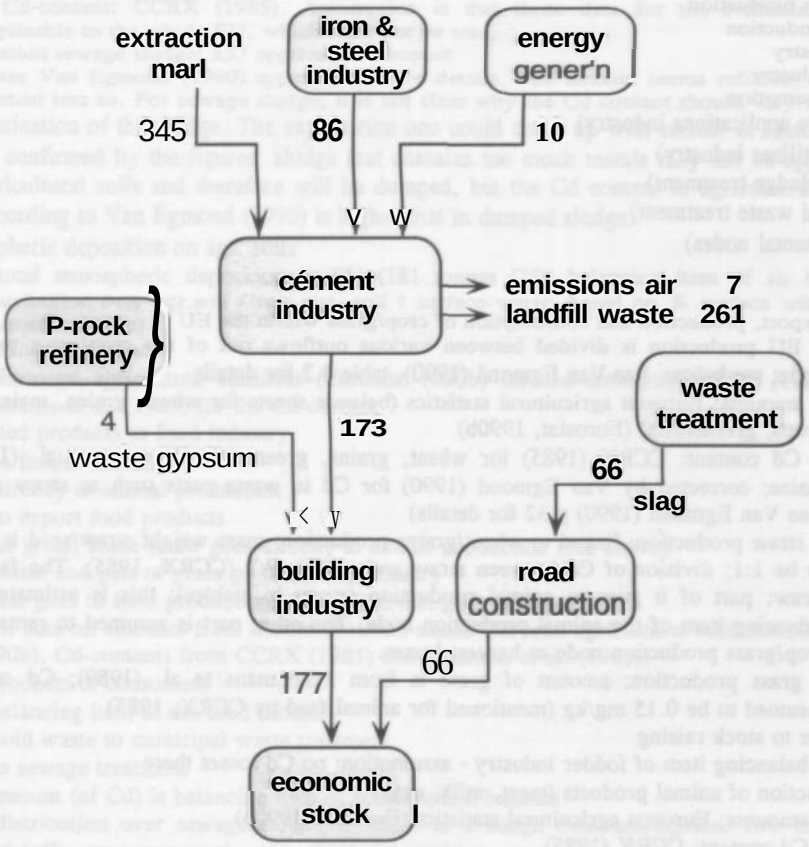
* assumption: all construction materials used in 1987 accumulate. Discarding from stock concerns materials applied in past years (see under the economic stock cluster).

x74 emissions air

x75 landfill solid waste

* figures from ERL (1989). These are flow figures, not emission factors; have been translated into emission factors by Van Egmond).

Figure A2.6 Flow chart building & road construction



1.7 Food production and consumption

nodes
crop/grass production
animal production
food industry
fodder industry
food consumption
(phosphate applications industry)
(other fertilizer industry)
(sewage sludge treatment)
(municipal waste treatment)
(environmental nodes)

flows
import, export, production and consumption of crop/grass within the EU
* EU production is divided between various outflows out of the crop/grass production node; see below. See Van Egmond (1990), table 4.2 for details.
* amounts: Eurostat agricultural statistics (balance sheets for wheat, grains, maize, fodder crops, greenstuffs) (Eurostat, 1990b)
* Cd content: CCRX (1985) for wheat, grains, greenstuff; Wiersma et al. (1985) for maize; corrected by Van Egmond (1990) for Cd in waste parts such as straw and leafs (see Van Egmond (1990) p 32 for details)
* straw production: linked to wheat/grains production; mass weight straw/seed is assumed to be 1:1; division of Cd between straw and seed is 9:1 (CCRX, 1985). The fate of the straw: part of it goes to animal production (straw in stables); this is estimated as the balancing item of the animal production node. The other part is assumed to remain in the crop/grass production node as harvest losses.
* grass production: amount of grass is from Ackermans te al. (1989); Cd content is assumed to be 0.15 mg/kg (mentioned for animal feed by CCRX, 1985)

x71 fodder to stock raising
* balancing item of fodder industry - assumption: no Cd losses there

x67 production of animal products (meat, milk, eggs)
* amounts: Eurostat agricultural statistics (Eurostat, 1990b)
* Cd content: CCRX (1985).
* is only a minor amount. The bulk of the ingested Cd ends up in manure (low retaining of Cd). See Van Egmond (1990) table 4.3 for details.

x35 application P fertilizer

x36 application P fodder additive

x26 application waste gypsum in agriculture
* see phosphate production and consumption

x55 application other fertilizer
* amount: OECD statistics (OECD, 1991)
* Cd content: Van Egmond (1990), appendix 2.1
* nitrogen and potassium industrial fertilizer also appear to contain Cd. It is not clear how it gets there, since there seems to be no opportunity for the Cd to be introduced. Possibilities are through methane or through atmospheric deposition. This implies that the amount of Cd involved in this, 43 tonnes, cannot be accounted for, i.e. related to an inflow into the system. It is therefore booked as an import.

x68 production/application manure
* amounts per type of animal: see Van Egmond table 3.2, from Ackermans et al. (1989).

Although this seems rather reliable for data of this sort, it would still imply a margin of error of 50%. Errors in this figure may have a great influence, especially since it is a large amount and part of a cycle.

* Cd-content: CCRX (1985). Assumption is that these data for the Netherlands are applicable to the whole EU, which need not be true.

x56 application sewage sludge; x57 application compost

* see Van Egmond (1990) appendix 3.3 for details. The amount seems reliable, the Cd-content less so. For sewage sludge, it is not clear why the Cd content should vary with the destination of the sludge. The explanation one could come up with seems, at least, not to be confirmed by the figures: sludge that contains too much metals may not be applied to agricultural soils and therefore will be dumped, but the Cd content in agricultural sludge according to Van Egmond (1990) is higher that in dumped sludge.

x96 atmospheric deposition on agr. soils

* total atmospheric deposition in EU (181 tonnes Cd): balancing item of air balance. Distribution over agr.soil / non agr. soil / surface water: based on % surface within EU (Eurostat, 1990a)

x70 import fodder products

* Eurostat agricultural statistics (Eurostat 1990b) for the amounts, CCRX (1985) and Wiersma et al. (1985) for the Cd content

x62 harvested products to food industry

x69 idem to fodder industry

x66 idem directly to animal production

x58 idem to export food products

* all grass, some straw goes directly to animal production (see above)
* maize and part of grain go to fodder industry
* rest goes to food production, fraction of that goes to export
* all data on amounts from detailed balance sheets Eurostat agricultural statistics (Eurostat, 1990b), Cd-contents from CCRX (1985) and Wiersma et al. (1985).

x63 food products to consumers

* balancing item of the food industry

x64 household waste to municipal waste treatment

x65 idem to sewage treatment

* amount (of Cd) is balancing item of consumption balance
* distribution over sewage/municipal waste is a rough own assumption: two thirds of foodstuffs are consumed, one third is cookery waste and leftovers. This implies, incidentally, that only a small amount of Cd in compost is due to vegetable and fruit waste (8 out of 28), and therefore the remainder must be due to back yard waste. This is possible, but disappears in the municipal waste balance. In retrospect, it would have been better to have established a connection between non-agricultural soil and municipal waste of 24 ktonnes Cd, which then represents the back yard waste fraction of compost.

x59 emissions air

* the estimate of 35 tonnes from vegetation was the average between the two extremes: 2.7 and 68 tonnes, calculated according to Beauford (Cd/Zn ratio) and Nriagu (Cd emission per square kilometer) respectively. See Van Egmond (1990) p 34 for details.

x60 emissions surface water

* runoff; assumption: 1 % of total inflow into agr.soils minus harvest. Van Egmond (no source mentioned, but based on Dutch figures. Probably from Van der Voet et al., 1989).

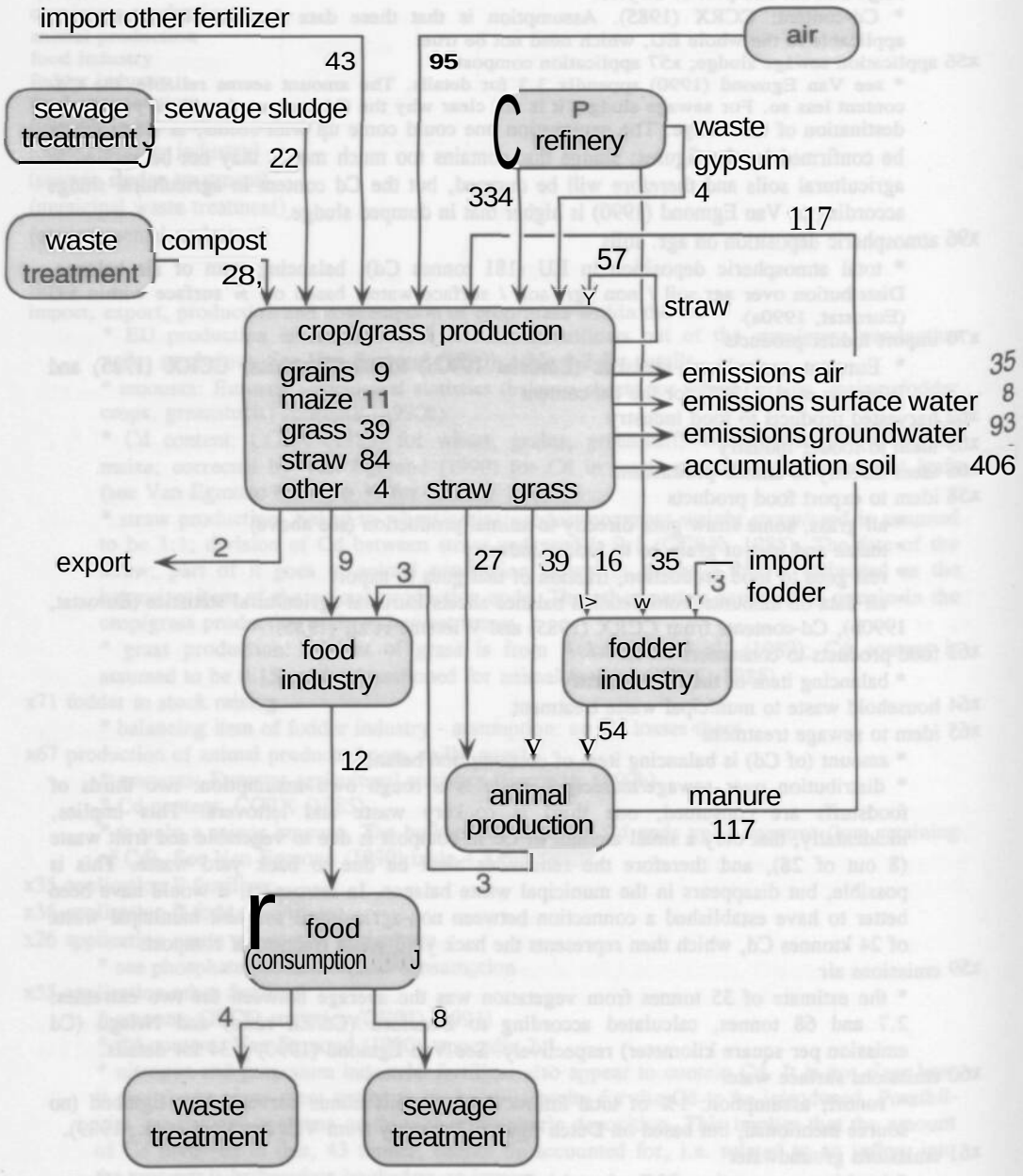
x61 emissions groundwater

* leaching; assumption: 20% of total inflow agr. soils minus harvest. Van Egmond, idem.

x159 accumulation in agricultural soils

* balancing item of crop/grass production balance; no data available.

Figure A2.7 Flow chart food production and consumption



1.8 Municipal waste treatment

nodes
municipal waste treatment
(economic stock)
(use cadmium applications)
(use phosphate applications)
(use fossil fuel applications)
(food consumption)
(crop/grass production)
(road construction)
(zinc refinery)
(iron refinery)
(environmental nodes)

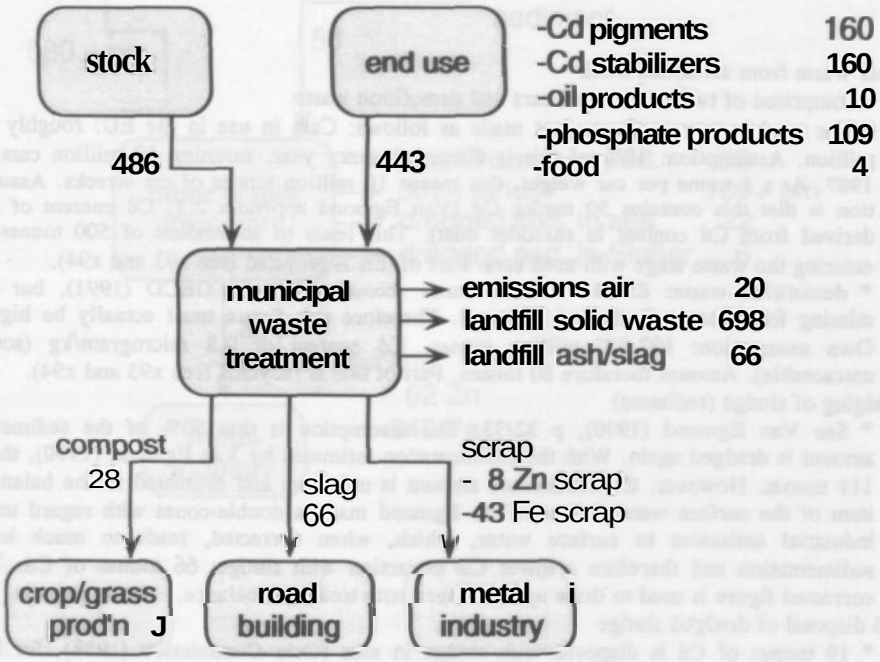
flows
x34 discarding of P-products
* see phosphate balance
x50 discarding of oil based products
* see fossil fuels balance
x64 cookery waste and leftovers
* see food production and consumption balance
x130 discarded products containing Cd pigments
* see cadmium applications balance
x136 discarded products containing Cd stabilizers
* see cadmium applications balance
x81 discarded products from economic stock
* unknown, estimated by extracting the total of the above (443 tonnes of Cd) from the total estimated Cd amount in municipal waste (929 tonnes of Cd), and therefore as the balancing item of the municipal waste node. The estimate for the total amount of Cd in municipal waste is based on OECD data regarding the generation of municipal waste (OECD, 1991), and an assumption of 10 mg/kg for the Cd content of this waste (ERL, 1989). Other figures are mentioned for the Cd-content as well, mostly lower ones: 4 mg/kg (RIVM Basisdocument) or even less. All in all, this figure is highly uncertain.
treatment and destination of municipal waste
* this is treated extensively by Van Egmond (1990) in appendix 3.3, details on p 18/19. The starting point is the amount of Cd in municipal waste; an estimate is made with regard to the distribution factors over the various treatment options: landfill, composting, and incineration, as well as with regard to the destination of the Cd in incinerated waste: landfill of ashes and slag, use of slag in road construction, recycling of scrap, and air emissions. Van Egmond based these distributions on the OECD statistics (OECD, 1991).
x13 and x95 recycling Zn and Fe scrap
* see under zinc production and use
x57 compost
* see under food production and consumption; assumption is that this will all be used on agricultural soil. This assumption is obviously wrong but since it concerns a minor amount no extensive data search has been performed to obtain an estimate of this flow.
x78 slag used for road construction
* see under building and road construction
x83 air emissions waste incineration
* emission factor of 1 g/tonne incinerated waste based on various estimates varying

between 0.5 and 2.25 g/tonne (see Van Egmond, 1990).

x84 landfill of final waste

* is comprised of two items: the landfill of municipal waste, and the landfill of waste incineration residues. See above.

Figure A2.8 Flow chart municipal waste treatment



1.9 Other waste treatment

nodes
other waste treatment
(economic stock)
(zinc refinery)
(iron refinery)
(environmental nodes)

flows
x82 other waste from economic stock

* comprised of two items: used cars and demolition waste
* For used cars an estimate was made as follows: Cars in use in the EU: roughly 100 million. Assumption: 10% of this is discarded every year, meaning 10 million cars for 1987. At a 1 tonne per car weight, this means 10 million tonnes of car wrecks. Assumption is that this contains 50 mg/kg Cd (Van Egmond appendix 2.1, Cd content of cars derived from Cd content in shredder dust). This leads to an amount of 500 tonnes Cd entering the waste stage with used cars. Part of this is recycled (see x93 and x94).
* demolition waste: 85.324 million tonnes accounted for by OECD (1991), but data missing for Greece, Spain and Portugal. Therefore this figure must actually be higher. Own assumption: 100.000 million tonnes. Cd content of 0.8 microgram/kg (source untraceable). Amount therefore 80 tonnes. Part of this is recycled (see x93 and x94).

x97 dredging of sludge (sediment)

* See Van Egmond (1990), p 32/33. The assumption is that 50% of the sedimented amount is dredged again. With the sedimentation estimated by Van Egmond (1990), this is 111 tonnes. However, the sedimented amount is unknown and estimated as the balancing item of the surface water balance. Van Egmond made a double-count with regard to the industrial emissions to surface water, which, when corrected, leads to much lower sedimentation and therefore a lower Cd extraction with sludge: 66 tonnes of Cd. This corrected figure is used to draw up the other waste treatment balance.

x85 x86 disposal of dredged sludge

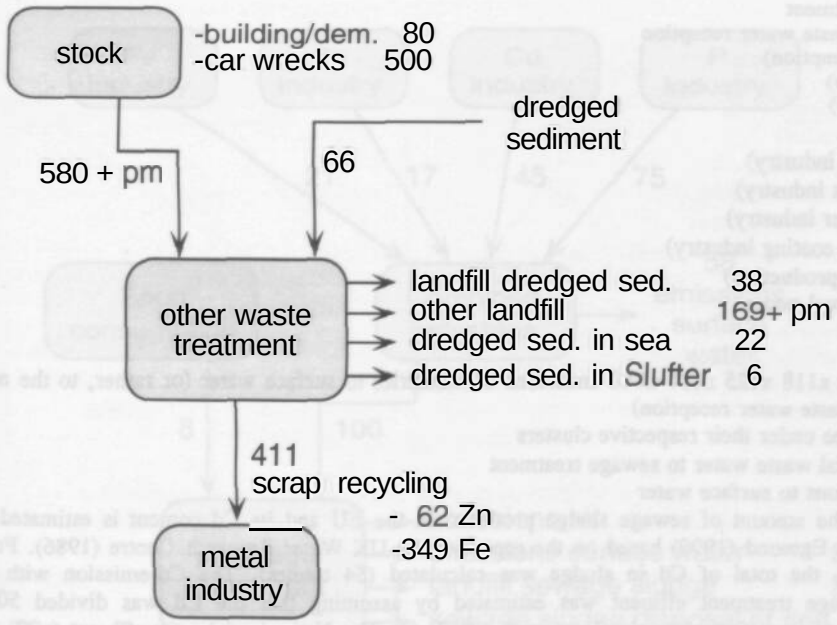
* 19 tonnes of Cd is disposed with sludge in seas (Oslo Commission (1988), for both amount and Cd content). Why this has become 22 tonnes in CDEUR55X is unclear. Probably a mistake, an uncorrected distribution factor or some similar explanation.
* 6 tonnes Cd with sludge in Slufter: estimate by Van Egmond (1990) based on data for The Netherlands.
* landfill of sludge: is part of x87, balancing item of sludge balance.

x93 x94 recycling of Fe and Zn. See under Zn production and use.

x87 landfill of other waste

* unknown, balancing item of the other waste treatment node.

Figure A2.9 Flow chart other waste treatment



1.10 Sewage treatment

nodes

sewage treatment
industrial waste water reception
(food consumption)
(Zn refinery)
(Fe refinery)
(P refinery)
(Cd battery industry)
(Cd pigment industry)
(Cd stabilizer industry)
(Cd surface coating industry)
(crop/grass production)
(environmental nodes)

flows

x7 x28 x40 x118 xl25 xl37 x140 emissions of industries to surface water (or rather, to the node industrial waste water reception)

* See under their respective clusters

x98 industrial waste water to sewage treatment

x169 emissions to surface water

* The amount of sewage sludge produced in the EU and its Cd content is estimated by Van Egmond (1990) based on the report of the UK Water Research Centre (1986). From that, the total of Cd in sludge was calculated (54 tonnes). The Cd-emission with the sewage treatment effluent was estimated by assuming that the Cd was divided 50/50 (assumption from Van der Voet et al (1989) for The Netherlands) over effluent (x90) and sewage sludge. The total output of the sewage treatment thus is 54 * 2 = 108 tonnes of Cd. The total input that could be accounted for was only 8 tonnes (from food consumption). This can be explained by the fact that a part of the industrial waste water is treated before it is emitted. A hypothetical node "industrial waste water reception" was created, comprising all the industrial waste water flows and channeling 100 tonnes off to sewage treatment, this being the deficit on the sewage water balance. The remainder is then emitted to the surface water. This results in a different estimate compared to the estimate by Van Egmond (1990), in fact to considerably lower emissions to surface water.

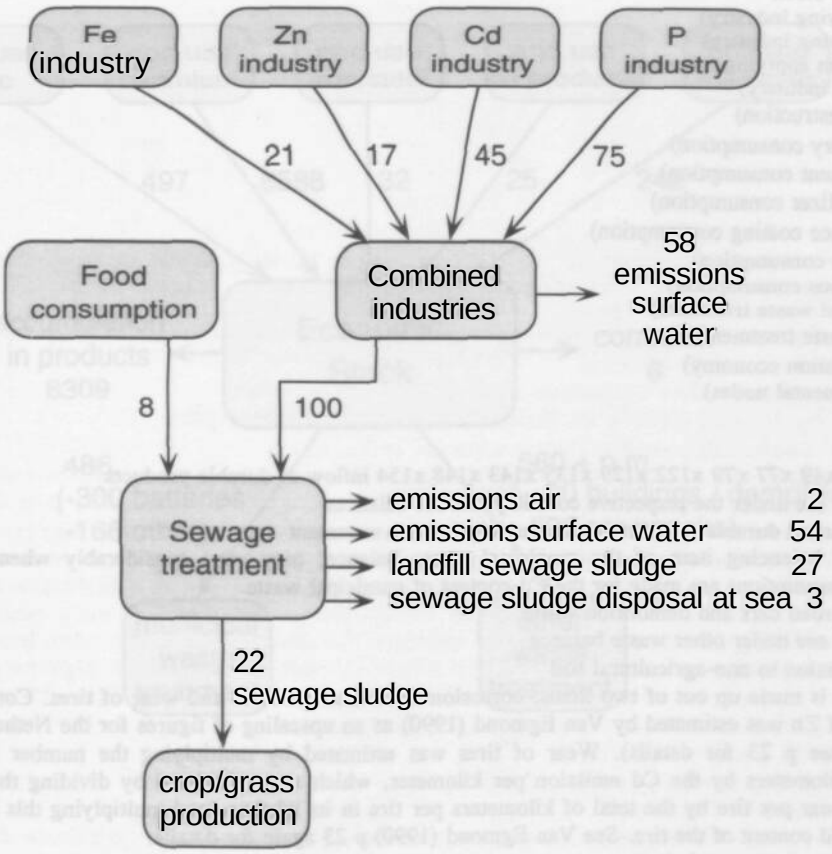
x56 x88 x89 x90 x91

* The sludge has various destinations: incineration (x89 air emission, emission factor of 20%, remaining 80% is dumped with ashes), use as a fertilizer on agricultural soils (x56), disposal at sea (x88), and landfill (x91). The amounts (sludge and Cd-content) are derived from the UK Water Research Centre report (1986). See Van Egmond (1990), appendix 3.3 p 14-17, for details.

x65 human waste to sewage treatment

* see under food consumption and production

Figure A2.10 Flow chart sewage sludge treatment



1.11 Economie stock

nodes

economic stock
(Zn applying industry)
(Fe applying industry)
(petroleum applying industry)
(building industry)
(road construction)
(Cd battery consumption)
(Cd pigment consumption)
(Cd stabilizer consumption)
(Cd surface coating consumption)
(Cd alloy consumption)
(Cd various consumption)
(municipal waste treatment)
(other waste treatment)
(accumulation economy)
(environmental nodes)

flows

xl2 x34 x49 x77 x79 xl22 xl29 xl35 xl43 xl48 xl54 inflow of durable products

* see under the respective consumption/use balances

x81 discarded durable applications to municipal waste treatment

* balancing item of the municipal waste balance; may vary considerably when other assumptions are made for the Cd content of municipal waste.

x82 discarded cars and demolition waste

* see under other waste balance

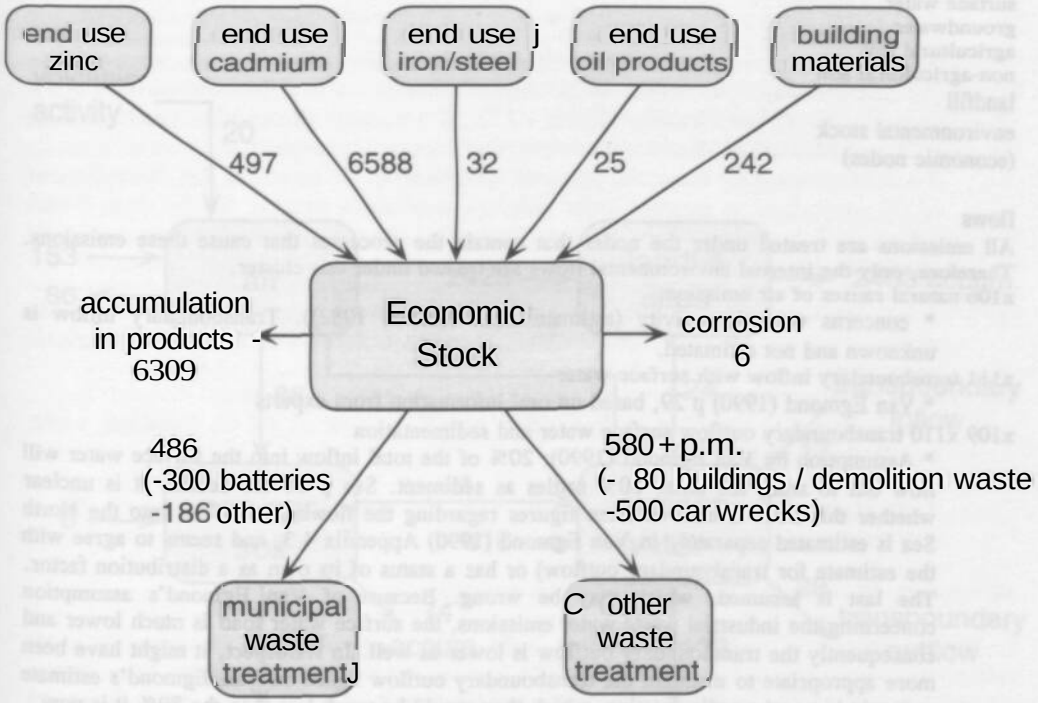
xl61 emission to non-agricultural soil

* is made up out of two items: corrosion from zinc products and wear of tires. Corrosion of Zn was estimated by Van Egmond (1990) as an upscaling of figures for the Netherlands (see p 23 for details). Wear of tires was estimated by multiplying the number of car kilometers by the Cd emission per kilometer, which was calculated by dividing the total wear per tire by the total of kilometers per tire in its lifetime, and multiplying this by the Cd content of the tire. See Van Egmond (1990) p 23 again for details.

x155 economic accumulation

* balancing item of the economic stock node. Is a very large number. There are no data whatsoever about this. It currently appears that a very large part of the inflow into this node accumulates, since the disposal of waste is small compared to the inflow. A different assumption regarding the cadmium content in municipal and other waste may influence this accumulation significantly.

Figure A2.11 Flow chart economic stock



1.12 Environment

nodes
air
surface water
groundwater
agricultural soil
non-agricultural soil
landfill
environmental stock
(economic nodes)

flows
All emissions are treated under the nodes that contain the processes that cause these emissions. Therefore, only the internal environmental flows are treated under this cluster.

x106 natural causes of air emission
* concerns volcanic activity (estimate from Hutton, 1982)). Transboundary inflow is unknown and not estimated.

x111 transboundary inflow with surface water
* Van Egmond (1990) p 29, based on oral information from experts

x109 x110 transboundary outflow surface water and sedimentation
* Assumption by Van Egmond (1990): 20% of the total inflow into the surface water will flow out to seas, the other 80% settles as sediment. See p 31 for details. It is unclear whether this 20% is derived from figures regarding the flows (the inflow into the North Sea is estimated separately in Van Egmond (1990) Appendix 4.3, and seems to agree with the estimate for transboundary outflow) or has a status of its own as a distribution factor. The last is assumed, which may be wrong. Because of Van Egmond's assumption concerning the industrial waste water emissions, the surface water load is much lower and consequently the transboundary outflow is lower as well. In retrospect, it might have been more appropriate to maintain the transboundary outflow figure on Van Egmond's estimate and only lower the sedimentation, which then would be much less than the 80% it is now.

x96 xl07 x160 atmospheric deposition
* see food production and consumption balance

x60 x162 xl08 runoff from soils
* estimate: 1 % of surplus of soil balance, for agricultural and non-agricultural soils as well as landfill sites. Based on Van der Voet et al. (1989). Very uncertain figure. See also food production and consumption balance.

x61 xl63 leaching to groundwater
* assumption: 20% of input in soils (both agricultural and non-agricultural) leaches to the groundwater. Uncertain figure, see food production and consumption balance.

x156 accumulation in ground water
* assumption: all of the inflow accumulates. Probably untrue, but any other assumption cannot be validated. A flow that certainly does exist is the extraction of ground water for drinking purposes. No estimate available. Nor is there an estimate for the transportation of groundwater and the seepage that occurs, and the amount of time it takes before leached Cd will emerge again.

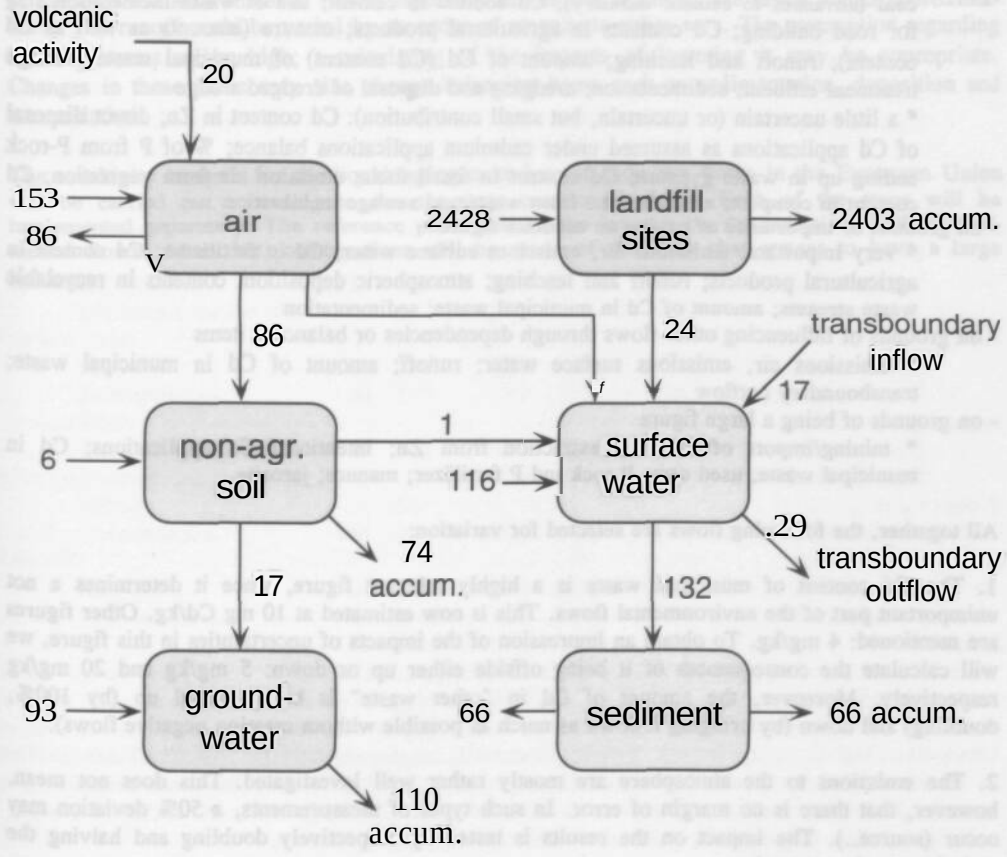
x97 x157 fate of sediment
* see under other waste balance, assumption: 50% accumulates, 50% is dredged.

x158 accumulation on landfill sites
* balancing item of landfill node, 99% of inflow (1% is assumed to runoff to the surface water).

x165 accumulation non-agricultural soil

* balancing item of the non-agricultural soil balance.

Figure A2.12 Flow chart environment



1.13 **Conclusions:** which data will be varied in a sensitivity analysis?

Based on the criteria mentioned in section 1.1, the following flows apply:

- on grounds of uncertainty
  * uncertain: scrap recycling (amount as well as Cd content); Cd content in phosphate rock and products; Cd content in Fe ore, products and especially scrap; destination of Cd in coal (air/ashes to cement industry); Cd content in cement; use of waste incineration slag for road building; Cd contents in agricultural products; manure (amounts as well as Cd content); runoff and leaching; amount of Cd (Cd content) of municipal waste; sewage treatment effluent; sedimentation; dredging and disposal of dredged sludge
  * a little uncertain (or uncertain, but small contribution): Cd content in Zn; direct disposal of Cd applications as assumed under cadmium applications balance; % of P from P-rock ending up in waste gypsum; Cd content in fossil fuels; emission air from vegetation; Cd content in compost; air emissions from waste and sewage incineration
- on grounds of importance of having an accurate figure
  * very important: emissions air, emissions surface water; Cd in fertilizers; Cd content in agricultural products; runoff and leaching; atmospheric deposition; contents in recyclable waste streams; amount of Cd in municipal waste; sedimentation
- on grounds of influencing other flows through dependencies or balancing items
  * emissions air, emissions surface water; runoff; amount of Cd in municipal waste; transboundary outflow
- on grounds of being a large figure
  * mining/import of Zn; Cd extraction from Zn; intentional Cd applications; Cd in municipal waste; used cars; P rock and P fertilizer; manure; jarosite

All together, the following flows are selected for variation:

1. The Cd content of municipal waste is a highly relevant figure, since it determines a not unimportant part of the environmental flows. This is now estimated at 10 mg Cd/kg. Other figures are mentioned: 4 mg/kg. To obtain an impression of the impacts of uncertainties in this figure, we will calculate the consequences of it being offside either up or down: 5 mg/kg and 20 mg/kg respectively. Moreover, the amount of Cd in "other waste" is being varied up (by 100%, doubling) and down (by bringing it down as much as possible without creating negative flows).

2. The emissions to the atmosphere are mostly rather well investigated. This does not mean, however, that there is no margin of error. In such types of measurements, a 50% deviation may occur (source..). The impact on the results is tested by respectively doubling and halving the emissions to the atmosphere.

3. The construction regarding the sewage treatment is the third important issue for a sensitivity analysis. Now we'll assume that the emissions as Van Egmond investigated really are emissions to the surface water, and that *on top of that* 100 tonnes of Cd flow from the industries to the sewage water treatment. This would considerably increase the surface water emissions. It will also have impacts on the balances for the industries. The landfill items may even disappear.

4. The scrap balance and the Fe balance are related. Any changes in the Fe balance must have consequences for the scrap. The Zn scrap is less dependent on this, since data are available on Cd contents as well as amounts of Zn scrap. In view of the strange Fe balance, we will vary the Cd content in both ore (by a factor 2) and Fe products (by an order of magnitude).

5. The crop/grass balance is one of the best investigated balances. It is however a very important balance from the point of view of environmental and health risks. The addition to it by P fertilizer is an important inflow. In order to test the impacts of uncertainties in the Cd content data, this will be varied by a factor 2 up and down. On the other hand, the extraction of Cd with harvested crop and grass is varied by a factor 2 up and down to estimate the consequences of deviations on the outflow side for the environmental flows.

6. Some of the environmental flows, especially runoff and leaching, are rather rough approximations. The runoff could be varied by an order of magnitude either way. The assumption regarding leaching seems rather high; a calculating of the impacts of lowering it may be appropriate. Changes in these flows may also change balancing items such as sedimentation, deposition and accumulation.

The sensitivity analysis for the bookkeeping overview of cadmium flows in the European Union will be carried out according to the six steps mentioned above. Each of the steps will be implemented separately. The reference point will be the impacts on the emissions and environmental flows. After that, combinations will be made of the steps that appear to have a large influence.

1.14 Results of the sensitivity analysis

1.14.1 Municipal and other waste

The amount of Cd in municipal and other waste is doubled (CDEUR551.SFA) and halved (CDEUR155.SFA).

Table A2.1 The influence of modifications in the Cd content of waste streams on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR551	CDEUR155
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6306	4862	6957
Agricultural soil			
Inflow	689	727	669
Animal manure	117	117	117
Accumulation	406	442	388
Air			
Inflow	172	192	161
Deposition on agr.soil	85	95	80
Surface water			
Inflow	160	175	154
Sedimentation	132	143	126
Groundwater			
Accumulation	112	116	110
Non-agricultural soil			
Inflow	94	104	89
Accumulation	75	83	71
Landfill			
Inflow	2428	3828	1800
Accumulation	2403	3790	1782

All together, a shift can be detected between economic accumulation and landfill. The influence on the environmental flows of doubling or halving the total amount of Cd in waste seems to be limited, 10 - 15% at the most. The error in outcome caused by a possible error in the Cd content in waste therefore appears to be acceptable, although certainly significant.

1.14.2 Atmospheric emissions

Industrial emissions into the atmosphere are doubled (CDEUR255.SFA) and halved (CDEUR552.SFA).

Table A2.2 The influence of modifications in industrial emissions into the atmosphere on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR255	CDEUR552
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6306	6306	6306
Agricultural soil			
Inflow	689	746	661
Animal manure	117	117	117
Accumulation	406	451	384
Air			
Inflow	172	287	114
Deposition on agr.soil	85	142	58
Surface water			
Inflow	160	162	160
Sedimentation	132	133	132
Groundwater			
Accumulation	112	135	101
Non-agricultural soil			
Inflow	94	151	66
Accumulation	75	119	52
Landfill			
Inflow	2428	2314	2486
Accumulation	2403	2291	2461

Here, the trade-off seems to be between air emissions and landfill. Larger air emissions result in slightly larger environmental flows, but the effect in the other environmental compartments seems rather limited, although the air load is assumed to be distributed entirely over the other compartments, with the exception of the non-agricultural soil. The principal impact, therefore, is at the point where it could be expected: in the air load, which varies up or down by about a third.

1.14.3 Sewage treatment and industrial waste water

In CDEUR553.SFA the modifications as described in Section 2.1.12 are made.

Table A2.3 The influence of modifications in the sewage treatment assumptions on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR553
	Amount (tonnes Cd/y)	
Flow		
Economic accumulation	6306	6306
Agricultural soil		
Inflow	689	689
Animal manure	117	117
Accumulation	406	406
Air		
Inflow	172	172
Deposition on agr.soil	85	85
Surface water		
Inflow	160	282
Sedimentation	132	232
Groundwater		
Accumulation	112	112
Non-agricultural soil		
Inflow	94	94
Accumulation	75	75
Landfill		
Inflow	2428	2335
Accumulation	2403	2312

The trade-off here is between surface water emissions and landfill. There is no influence on the other environmental compartments, with the exception, of course, of sedimentation. The surface water load and also sedimentation, outflow to the seas, and the amount in dredged sludge, are therefore modified significantly.

1.14.4 Fe and scrap

In CDEUR554.SFA the amount of Cd in iron ore, as well as iron and steel material and products, is assumed an order of magnitude higher.

Table A2.4 Influence of a higher Cd-content in Fe-products and raw materials on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR554
	Amount (tonnes Cd/y)	
Flow		
Economic accumulation	6306	6594
Agricultural soil		
Inflow	689	689
Animal manure	117	117
Accumulation	**406**	**406**
Air		
Inflow	172	172
Deposition on agr.soil	85	85
Surface water		
Inflow	160	160
Sedimentation	132	132
Groundwater		
Accumulation	112	112
Non-agricultural soil		
Inflow	94	94
Accumulation	75	75
Landfill		
Inflow	2428	2323
Accumulation	2403	2300

The amount of Cd in Fe that needs to be recycled in order to fit the balance does not change a great deal, although it is somewhat higher (454 instead of 349 tonnes of Cd). This has no influence at all on the environmental flows; there is only a relatively minor shift from landfill to economic accumulation. The effects on the total balance of the Fe node being out of balance would therefore appear to be limited.

1.14.5 The crop/grass balance

The amount of Cd in P is doubled in CDEUR55V.SFA. In CDEUR55W.SFA, the extracted amount of Cd with crop and grass is doubled. In CDEUR555.SFA, these two alterations are combined.

Table A2.5 The influence of different assumptions regarding the Cd-content in P-products and raw materials and in crop/grass products on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR55V	CDEUR55W	CDEUR555
	Amount (tonnes Cd/y)			
Flow				
Economic accumulation	6306	6318	6306	6318
Agricultural soil				
Inflow	689	1067	830	1207
Animal manure	117	152	198	233
Accumulation	406	712	397	702
Air				
Inflow	172	174	172	174
Deposition on agr.soil	85	86	85	86
Surface water				
Inflow	160	241	165	245
Sedimentation	132	198	135	201
Groundwater				
Accumulation	112	180	112	180
Non-agricultural soil				
Inflow	94	95	94	95
Accumulation	75	75	75	75
Landfill				
Inflow	2428	2640	2435	2647
Accumulation	2403	2614	2411	2620

The cadmium content in phosphate appears to be important for the environmental flows. Doubling the Cd-content has an almost one-to-one impact on the agricultural soil, and therefore also on both the groundwater and the surface water, and thus also on sedimentation. This works through fertilizer on the one hand, and the emissions from the phosphate industry on the other, which contribute significantly to the surface water load even without the doubling of the P-content. It can be concluded, therefore, that it is important to have reliable information on the Cd-content of P raw materials and products. The amount of Cd in animal manure is influenced by both the P and the crop/grass assumption. Although the amount of 117 tonnes Cd in reality is a figure from literature, in the CDEUR55*.SFA series it is entered as the balancing item of the stock raising balance. As a figure from literature, it has margins of error of its own. It cannot be varied separately, however, in the present bookkeeping system.

1.14.6 Runoff and leaching

In CDEUR556.SFA, the runoff percentage is lowered from 1% of the (net) soil load to 0.1%. At the same time, the leaching percentage is lowered from 20% of the (net) soil load to 2%. In CDEUR655.SFA, the reverse effect is tried for runoff: 5% of the (net) soil load is assumed instead of 1 %. The leaching percentage is not tried out at a higher level since it appears to be very high already.

Table A2.6 The influence of different assumptions regarding the leaching and runoff fractions on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR556	CDEUR655
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6306	**6306**	**6306**
Agricultural soil			
Inflow	689	689	689
Animal manure	117	117	117
Accumulation	406	494	388
Air			
Inflow	172	172	172
Deposition on agr.soil	85	85	85
Surface water			
Inflow	160	134	282
Sedimentation	132	110	231
Groundwater			
Accumulation	112	11	112
Non-agricultural soil			
Inflow	94	94	94
Accumulation	75	92	71
Landfill			
Inflow	2428	2422	2458
Accumulation	2403	2420	2335

The trade-off here is between accumulation in soils and on landfill sites on the one hand, and groundwater/surface water/sedimentation on the other. The variation in the runoff has an especially large influence on the surface water. It appears that, while the contribution of runoff from landfill is almost invisible if we assume a value of 0.1%, it makes the largest inflow into the surface water, with 5%. The impact on the landfilled waste is naturally much lower, since the runoff in a relative sense is still low at 5%. In view of the importance of these processes for the environmental flows, the complete lack of data and knowledge regarding them is regrettable, to say the least.

1.14.7 Combination 1: maximizing the soil load

In CDEUR557.SFA, the assumptions regarding the Cd content of municipal waste, the Cd content of P, and the runoff and leaching are combined to investigate the extents to which the soil balances (agricultural, non-agricultural and landfill) would be stretched if all error margins would work in the same direction: maximizing the soil load and accumulation. This means: doubling the Cd content in municipal waste and in P, and decreasing the runoff to 0.1% and the leaching to 2%. This combination leads to the following:

Table A2.7 The influence of the combined changes in assumptions regarding the Cd-content in municipal waste, the Cd content in P products and raw materials, and the runoff and leaching fractions on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR557
	Amount (tonnes Cd/y)	
Flow		
Economic accumulation	6306	5454
Agricultural soil		
Inflow	689	1104
Animal manure	117	152
Accumulation	406	902
Air		
Inflow	172	194
Deposition on agr.soil	85	96
Surface water		
Inflow	160	210
Sedimentation	132	172
Groundwater		
Accumulation	112	18
Non-agricultural soil		
Inflow	94	105
Accumulation	75	103
Landfill		
Inflow	2428	3449
Accumulation	2403	3446

The accumulation in agricultural soil thus has slightly more than doubled. The accumulation on landfill sites has increased considerably, by over a 1000 tonnes, being somewhat under 50% of the original accumulation. The accumulation in non-agricultural soils has increased by roughly a quarter. This occurs at the expense of economic accumulation, which has become roughly the same size as the total of environmental accumulations, while it was twice that size originally.

1.14.8 Combination 2: maximizing the surface water load

In CDEUR558.SFA, the surface water load is maximized by a similar approach. This time, the sewage water assumption from CDEUR553.SFA is combined with doubling the Cd content in P and increasing runoff to 5% of the (net) soil load. The effect is the following:

Table A2.8 The influence of the combined changes in assumptions regarding the Cd-content in P products and raw materials, and the runoff fraction on the Cd bookkeeping overview

Assumed regime	CDEUR55B	CDEUR558
	Amount (tonnes Cd/y)	
Flow		
Economic accumulation	6306	6318
Agricultural soil		
Inflow	689	1067
Animal manure	117	152
Accumulation	406	680
Air		
Inflow	172	174
Deposition on agr.soil	85	86
Surface water		
Inflow	160	494
Sedimentation	132	405
Groundwater		
Accumulation	112	180
Non-agricultural soil		
Inflow	94	95
Accumulation	75	75
Landfill		
Inflow	2428	2577
Accumulation	2403	2319

The surface water load, by combined efforts, can be tripled. The assumption regarding runoff is especially important, as mentioned before, because of its large influence and because of the lack of any data whatsoever about the magnitude of this flow.

1.15 Conclusions

In a bookkeeping system, data from widely varying sources are combined. For the economic flows, the following types of data generally are used:

1. Data regarding the amounts of raw materials and products, such as delivered by trade and production statistics. These data generally can be said to be relatively reliable. The only uncertainty concerns the accuracy with which companies fulfill their obligation of providing the statistics offices with their data. The margin of this uncertainty is unknown, but most probably minor since no important balance deficiencies occur. The CBS estimates an accuracy margin of well within 5% (Olsthoorn, oral communication).
2. Data regarding the content of the substance in the products or materials. The margins of error may be much larger here. It depends on the product/substance combination: for nitrogen in food products, the margins of error are much smaller than for cadmium in patent leather shoes. This is due partly to the intensity of monitoring, which is much larger for N than for Cd, partly to large differences in cadmium concentrations in both raw materials and specific products (Cd occurring as a contaminant, not intentionally used), and partly to the fact that Cd occurs in much lower concentrations in most applications. The higher the concentration, the more reliable the data are, in general.
3. Data regarding waste streams, mostly based on OECD estimates. The margins of error in these data are unknown, but probably considerable, since these statistics are usually incomplete or based on much older measurements. A margin of 50% up or down is quite possible.
4. Data regarding the Cd content in waste streams. These data are scarce and based on very crude estimates. A factor 2 uncertainty margin does not appear excessive.

For the environmental flows, emission factors and distribution coefficients are used in most cases. The emission factors can be regarded as relatively well investigated in the case of cadmium, although uncertainties up to 50% can be expected. The uncertainties in the environmental flows, especially runoff and leaching, are very large. In this case, a margin of an order of magnitude, a factor 10 either up or down, would not be impossible. These figures, therefore, are highly uncertain.

Bringing data with widely varying but sometimes large margins of error together limits the possibilities for basing statements on the bookkeeping overview of flows and stocks. The act of bringing them together, however, also increases those possibilities: attempting to establish a complete and coherent bookkeeping overview acts in itself as a powerful check. If a node appears to be completely out of balance, one is induced to look into the figures in more detail in order to spot the problem. Other flows can be estimated with more accuracy as a balancing item than based on measurements. This is especially true for accumulations (which, in fact, are not flows but rather stock modifications). Also, waste generation data can be checked in this way, as has been done for the "remaining waste" is the case of cadmium.

In order to obtain insight into the consequences for the overview of stocks and flows, a sensitivity analysis has been performed for a number of data. One should keep in mind that in this section the sensitivity analysis was conducted for the bookkeeping system. This means that in most cases, the changes that occurred in the overview as a result of different assumptions concerning one or more flows are not representative of causality, but only reflect the setup of the bookkeeping system. Exceptions to this are the environmental flows and some of the emissions, which are calculated with the help of distribution factors. Trade-offs therefore occur mostly through balancing items. It once more appears to be important which flows are chosen as balancing items. In the case of cadmium, almost invariably the unknown flows of either landfill or economic accumulation were chosen as balancing items. Any data uncertainties automatically are therefore shifted to landfill on the one hand and economic accumulation on the other. These large Cd sinks

are therefore the most insecure and are at greatest variance from the assumptions. However, their sheer magnitudes have a mitigating effect on their impacts: large changes in an absolute sense can be relatively small for these two flows.

There are some exceptions to this rule, especially related to "in-between" nodes which serve as distribution nodes for economic flows, without really representing production (or other) processes. These nodes do not have outflows to either landfill or economic stock. If changes are introduced in such nodes, other related flows must also be changed "by hand". This procedure was followed, for example, when introducing the changes regarding the Cd content in phosphate.

The bookkeeping overview therefore is rather robust against the influence of changes, which is also the case with the sensitivity analysis above. In almost all cases, the environmental flows (except landfill) are hardly influenced by changes in the economic flows. This may be different if we are dealing with the cadmium model, which is designed to calculate the impacts of changes. This will be addressed in Section 2 of this appendix. The Cd content in P raw materials and products and the assumption regarding runoff and leaching appear to have the greatest influence. The Cd content in P directly influences the agricultural soil balance and the surface water balance, and those two, in turn, influence the groundwater and sediment balances. The assumption regarding runoff, which is a distribution factor and not a figure from literature, has a large influence on the surface water balance, since the runoff from landfill sites could amount to a considerable quantity even if it is a relatively small amount, because of the magnitude of the amount of landfilled Cd. The same is true for leaching and groundwater.

Conclusions based on the bookkeeping overview, such as stated on p 120, 121 and 125 of Chapter 7, the cadmium case study, would appear to be rather robust and would still be valid under different assumptions for data fluctuations, such as those tried out above. Section 2 looks at the influence that bookkeeping errors in the cadmium model may exert on the conclusions based on that model.

2 Cadmium model

The cadmium model that is derived from the bookkeeping system is based on a number of assumptions. Some of these are tested in this section.

Choice for fixed variables and balancing items:
The system's sources are appointed as the fixed variables. In the light of cadmium's inelastic supply this seems to be a sensible choice. The scale level of the analysis, the European Union, is high enough to reduce the influence of imports and exports to an acceptable level. Although we know from Appendix 1 that a different choice for fixed variables might lead to different modelling results, it does not seem useful to test this in the case of cadmium. The same applies to the choice for the balancing items, which is also made in the most sensible way.

Steady state and stocks:
The cadmium model as it has been used in the case study does not represent a steady state situation, but represents the starting year 1987. The various regime changes in the shape of measures and measure packages have been introduced in the "National Environmental Outlook" manner, by introducing multiplication factors in the equations. Moreover, no stocks have been taken into account, in the first place because we didn't think of that at the time, but also because no stock data are available. Both may lead to erroneous outcomes. Therefore, two alternative models, representing the steady state situation and including stocks, are defined and the variations described below are tested on these as well. Additionally, one of the regime changes, the cadmium battery recycling, is put into the two steady state models. This provides some insight as to the value of the conclusions of the cadmium case study.

Distribution coefficients:
Different assumptions regarding the bookkeeping data may lead to different distribution coefficients. On the other hand, the system may be more sensitive for changes in one coefficient than in another. Keeping this in mind, the following coefficients are varied:
- on grounds of largest uncertainties: municipal waste. This will be treated in 4 different ways: first, a factor derived directly from CDEUR55B.SFA, the bookkeeping overview; second, a factor derived directly from CDEUR551.SFA, the bookkeeping overview wherein the average Cd-content of municipal waste is assumed to be twice as high; third, a factor derived from assumptions regarding the cadmium stock with users and the life time of the different applications in that stock; fourth, idem, but this time for the high Cd content in waste assumption.
- on grounds of channeling off small flows from large ones *and* uncertainty: runoff.
- on grounds of loops, also on grounds of the outcome of the theoretical exercise: the cadmium uptake coefficients of the agricultural processes.

The magnitude of the fixed variables:
The import of P-rock, the import and recovery of Zn ore, and the import of Cd appear from the origins analysis to be important parameters. The influence of changes in the magnitude of these is tested. Also, the test regarding influence of the Cd-content in Fe on the bookkeeping system will be performed for the model.

2.1 The steady state cadmium models

From the 1987 model CDEUR1.SFA, two steady state models are derived: CDEUR1C.SFA and CDEUR1D.SFA. In CDEUR1C.SFA, separate stocks are defined for all durable (i.e., with a life span longer than a year) cadmium applications. Newly produced applications automatically flow to the stocks. The disposal rate from the stocks is determined by the assumed life span. Stocks, with their life spans, are:

Cd in zinc applications	25 years (mostly building materials)
Cd in Fe applications	25 years (idem)
Cd in oil products (plastics)	5 years
Cd in cement	50 years
Cd in slag used in roads	15 years
Cd in batteries	5 years
Cd in pigments	2 years
Cd in stabilizers	10 years
Cd in surface coating	15 years
Cd in alloys	15 years
Cd in various	10 years.

In CDEUR1D.SFA, just one stock is created into which all durable applications flow. There is one disposal flow. In the formula used to calculate disposal from stock, the life span of some of the applications is included. Another difference between CDEUR1C and CDEUR1D is the recycling. In CDEUR1C it is assumed, that the Fe and Zn that is being recycled in the present situation more or less represents an equilibrium situation. This implies that the steady state model must render the same outcome as the 1987 model for the recycling flow. In CDEUR1D, this assumption was not made. The 1987 distribution factors have been implemented in the steady state model and lead to a recycling flow that is much larger. There is no easy way to ascertain which assumption is correct.

The outcome of both steady state models differs from the 1987 model, especially with regard to the generation of waste. In the following table, this is shown:

Table A2.9 Steady state of the 1987 cadmium regime according to the static models CDEUR1C and CDEUR1D

Assumed regime	CDEUR1	CDEUR1C	CDEUR1D
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6306	-	-
Economic stock	-	70733	90501
Municipal waste	930	5484	"5424
Other waste	647	2748	3481
Recycling	462	454	2680
Agricultural soil			
Inflow	690	929	1000
Animal manure	117	144	153
Crop/grass	93	125	134
Accumulation	406	545	587
Air			
Inflow	173	285	378
Deposition on agr.soil	85	141	187
Surface water			
Inflow	163	229	295
Sedimentation	132	187	242
Groundwater			
Accumulation	112	155	172
Non-agricultural soil			
Inflow	95	150	187
Accumulation	75	118	148
Landfill			
Inflow	2428	8516	8374
Accumulation	2403	8431	8291

Both steady state models, as expected, result in a higher level of the agricultural and environmental flows, CDEUR1D to a slightly greater degree than CDEUR1C.

2.2 Municipal waste

A change in the municipal waste assumption does not make any difference for the steady state models. The uncertainties in the amount of Cd in municipal waste have to do with not knowing how far we are (or were, in 1987) from an equilibrium situation. In the steady state models, the inflow determines the outflow and the equilibrium is established. Uncertainties in the present situation are therefore excluded. In the table below, therefore, only the 1987 models are compared. The assumption in CDEUR1B, the modified 1987 model, is that the amount of Cd in municipal and remaining waste is doubled. This is translated into a change in the distribution coefficients that determines the generation of waste from stock.

Table A2.10 The influence of modifications in the assumptions regarding the Cd content of waste streams on the Cd static modelling overview

Assumed regime	**CDEUR1** *Amount (tonnes Cd/y)*	CDEUR1B
Flow		
Economic accumulation	6306	4904
Economic stock	-	-
Municipal waste	930	1859
Other waste	647	1338
Recycling	462	994
Agricultural soil		
Inflow	690	479
Animal manure	117	121
Crop/grass	93	97
Accumulation	406	452
Air		
Inflow	173	217
Deposition on agr.soil	85	107
Surface water		
Inflow	163	190
Sedimentation	132	156
Groundwater		
Accumulation	112	121
Non-agricultural soil		
Inflow	95	118
Accumulation	75	93
Landfill		
Inflow	2428	3736
Accumulation	2403	3699

The changes are rather similar to the changes in CDEUR551 compared to CDEURB, as shown in 2.1.14.1, only in this case there is a slight increase in the agricultural flows which, naturally, does not show in the bookkeeping system. The most marked effects are on the economic accumulation (down) and the landfill (up), just as in the bookkeeping system.

2.3 Runoff

Since runoff is determined by a very uncertain coefficient which is not in any way sustained by measurements, the effects of changing this coefficient is calculated, both on the 1987 model and on the two steady state models. The outcomes of this are presented below, and must be compared with the table in 2.2.1 in order to get an impression of the direction and magnitude of the changes.

Table A2.11 The influence of modified assumptions regarding the runoff fraction on the CDEUR2* modelling overviews

Assumed regime	CDEUR2	CDEUR2C	CDEUR2D
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6306	-	-
Economic stock	-	70734	90501
Municipal waste	930	5484	5424
Other waste	675	2898	
Recycling	462	454	2680
Agricultural soil			
Inflow	690	929	1000
Animal manure	117	144	153
Crop/grass	93	125	134
Accumulation	388		
Air			
Inflow	173	285	378
Deposition on agr.soil	85	141	187
Surface water			
Inflow	281		
Sedimentation	231		
Groundwater			
Accumulation	112	155	172
Non-agricultural soil			
Inflow	95	150	187
Accumulation	71		
Landfill			
Inflow	2456	8516	8374
Accumulation	2334	8431	8291

Here, too, there is hardly any difference between CDEUR2 and CDEUR655 in 2.1.14.6, where the same change is applied to the bookkeeping system. The main change is that the inflow into surface water increases, leading to a higher sedimentation. Here, too, the runoff from landfill sites becomes the largest contributor to the surface water load. The effect is in the same direction, but magnified, in the two steady state models. This can be explained by the fact that the amount of landfilled Cd is much higher in these files.

2.4 The crop uptake of cadmium

In 1.2.14.5, the assumption of a higher cadmium uptake by crops was tested for the bookkeeping system. Here, it is tested for the cadmium models, by multiplying the distribution coefficients involved by a factor of 2. This leads to the following results, which can be compared with CDEUR1, CDEUR1C and CDEUR1D.

Table A2.12 The influence of modified assumptions regarding the Cd uptake by crops on the CDEUR4* modelling overviews

Assumed regime	CDEUR4	CDEUR4C	CDEUR4D
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	6307	-	-
Economic stock	-	70741	90520
Municipal waste	930	5484	5424
Other waste	675	2748	3481
Recycling	462	454	2680
Agricultural soil			
Inflow	814	1097	1000
Animal manure	225	291	153
Crop/grass	219	293	134
Accumulation	387	524	564
Air			
Inflow	180	294	387
Deposition on agr.soil	89	145	192
Surface water			
Inflow	169	237	305
Sedimentation	139	195	250
Groundwater			
Accumulation	109	151	167
Non-agricultural soil			
Inflow	98	154	192
Accumulation	77	122	151
Landfill			
Inflow	2437	8528	8387
Accumulation	2437	8443	8303

The increased cadmium uptake appears to have an intensifying impact on the agricultural cycle in all three models, possibly a little more for the steady state models than for the 1987 model. The increases are much larger than in the comparable bookkeeping system, which was to be expected, and are also much larger than in the case of doubling the cadmium inflow by phosphate (see next section), which is more remarkable. Apparently, the agricultural cycle provides a case of self reinforcing accumulation, wherein the impacts of the changes are intensified. This does not show in the bookkeeping system.

2.5 The system's cadmium sources: zinc, phosphate, and imported cadmium

CDEUR5 and CDEUR5C contain a doubling of the amount of Cd in phosphate. In CDEUR6 and CDEUR6C, the amount of Cd in zinc is doubled. In CDEUR7 and CDEUR7C, a doubling of the amount imported Cd is assumed. All three are combined in CDEUR8 and CDEUR8C. Since the CDEUR*C series seems to react in the same manner as the CDEUR*D series, no additional calculations were made for CDEUR*D.

A comparison of the 1987 models is presented in the next table:

Table A2.13 The influence of modifications in the assumptions regarding the Cd system's inflow in P, Zn and Cd products and raw materials on the 1987 Cd modelling overview

Assumed regime	CDEUR5	CDEUR6	CDEUR7	CDEUR8
	Amount (tonnes Cd/y)			
Flow				
Economic accumulation	6317	9148	9624	12476
Economic stock	-	-	-	-
Municipal waste	1042	1303	1360	1846
Other waste	676	1032	834	1248
Recycling	**469**	627	613	899
Agricultural soil				
Inflow	1189	746	722	1278
Animal manure	209	123	120	219
Crop/grass	160	100	97	172
Accumulation	698	438	424	750
Air				
Inflow	202	227	195	278
Depos. on agr.soil	100	112	96	137
Surface water				
Inflow	225	217	185	301
Sedimentation	184	178	152	247
Groundwater				
Accumulation	182	127	119	204
Non-agricultural soil				
Inflow	109	128	106	155
Accumulation	86	103	84	123
Landfill				
Inflow	2651	3744	3015	4554
Accumulation	2624	3707	2985	4509

The changes in the system's sources lead to significant changes in the waste, agricultural and environmental flows. The CDEUR8 seems to be a rather straightforward sum of the other three. We can see that most of the changes in the agricultural flows, as well as surface water, groundwater and sediment, are due to phosphate. Zinc is most important for air, non-agricultural soil and landfill. Cadmium has the greatest influence on the accumulation and the generation of municipal waste.

A comparison of the steady state models leads to the following picture:

Table A2.14 The influence of modifications in the assumptions regarding the Cd system's inflow in P, Zn and Cd products and raw materials on the steady state Cd modelling overview

Assumed regime	CDEUR5C	CDEUR6C	CDEUR7C	CDEUR8C
	Amount (tonnes Cd/y)			
Flow				
Economic accumulation	-	-	-	-
Economic stock	72552	107914	96743	134245
Municipal waste	5597	7591	8709	10930
Other waste	2784	4425	3630	5342
Recycling	454	904	454	904
Agricultural soil				
Inflow	1429	1083	1105	1758
Animal manure	237	162	165	275
Crop/grass	192	146	149	237
Accumulation	839	636	649	1032
Air				
Inflow	314	389	370	502
Depos. on agr.soil	155	192	183	249
Surface water				
Inflow	291	318	281	432
Sedimentation	238	260	231	355
Groundwater				
Accumulation	226	188	188	291
Non-agricultural soil				
Inflow	164	210	192	267
Accumulation	129	166	152	211
Landfill				
Inflow	8751	12576	12299	16593
Accumulation	8663	12450	12176	16427

Here too, the CDEUR8D file seems to be equal to the sum of the parts. Establishing the greatest influence in the changes, we can see a larger influence of zinc. Phosphate is still by far the most important for the agricultural flows and groundwater, but zinc is the most important for all the other flows, with the exception of municipal waste, for which cadmium still scores highest. Changes in the steady state model are magnified, compared to the 1987 model, but in the same direction.

2.6 Battery recycling

Battery recycling is one of the measures that is evaluated in the cadmium case study in Chapter 7. In regards to such cyclic processes especially, failing to base the conclusions on the steady state may lead to erroneous conclusions. Therefore, this measure is introduced in CDEUR1C and CDEUR1D as well, in order to see if the conclusions drawn in Chapter 7 are still valid.

Table A2.15 The influence of battery recycling on the Cd 1987 and steady state modelling overviews

Assumed regime	CDEUR6	CDEUR6C	CDEUR6D
	Amount (tonnes Cd/y)		
Flow			
Economic accumulation	9392	-	-
Economic stock		88581	122879
Municipal waste	1130	3455	3995
Other waste	684	3597	4906
Recycling	4542	4564	7809
Agricultural soil			
Inflow	710	832	966
Animal manure	119	133	149
Crop/grass	95	112	129
Accumulation	417	488	567
Air			
Inflow	188	243	391
Deposition on agr.soil	93	121	193
Surface water			
Inflow	186	238	343
Sedimentation	152	195	281
Groundwater			
Accumulation	116	138	169
Non-agricultural soil			
Inflow	102	129	193
Accumulation	81	102	153
Landfill			
Inflow	2765	7725	8355
Accumulation	2738	7647	8271

When comparing the CDEUR6* outcomes with the CDEUR1* ones, we see that the main change is in the same direction. CDEUR6 leads to a great increase in the economic accumulation, while CDEUR6C and CDEUR6D reveal an increased economic stock. However, a difference in reaction can be observed if we compare the changes in the agricultural and environmental flows of the 1987 model with those of the two steady state models. CDEUR6 leads to a slightly higher level of agricultural and environmental flows, while in CDEUR6C and CDEUR6D the level is just slightly lower. Whether these small changes are significant or not cannot be concluded from these models. Therefore, the conclusion could be rephrased as follows: the environmental and agricultural flows are barely influenced by introducing battery recycling. In retrospect, this is not surprising; in the 1987 model, everything appears to be translated into a higher economic accumulation, while nothing else could be expected for the steady state models according to the basic law IN = OUT. Therefore, the conclusions drawn in Chapter 7 regarding the influence of such measures (at least, of battery recycling) are still valid.

3 References

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APPENDIX 3 EVALUATION OF THE CASE STUDY "NITROGEN IN THE EUROPEAN UNION"

1 Bookkeeping data

Five clusters of processes are distinguished for nitrogen:
1. Nitrogen chemicals production
2. Food production
3. Wood and fossil fuels
4. Consumers and waste treatment
5. Environment.

In 1.1 to 1.5, the flows out of these clusters are discussed and the sources used to calculate them are mentioned.

In the table below, the overview of nitrogen flows in the EU is presented. The overview refers to the basic year 1988, the figures represent ktonnes N.

ITROG2.GVW

INPUTS OF fodder industry FROM:			
import agrprod for fodder	1342.0000	formula	x1
crop/grass production	2013.0954	formula	x26
food industry	76.0007	formula	x35
north sea	0.0000	formula	x110
==== Total =====	3431.0961		
OUTPUTS OF fodder industry TO:			
animal production	3087.9865	formula	x21
sewage treatment	171.5548	formula	x39
surface water	108.5599	bal.item*	x40
north sea	62.9949	formula	xll6
==== Total =====	3431.0961		
INPUTS OF food industry FROM:			
import agrprod for food	268.0000	formula	x2
animal production	1685.0151	formula	x24
crop/grass production	1284.0218	formula	X28
north sea	266.0000	formula	X109
==== Total =====	3503.0369		
OUTPUTS OF food industry TO:			
households	**2850.0000**	formula	x34
fodder industry	76.0007	formula	x35
export agrprod for food	226.7325	bal.item*	X36
sewage treatment	175.1518	formula	x37
surface water	111.1514	formula	x38
north sea	64.0005	formula	xll5
==== Total =====	3503.0369		

INPUTS OF wood industry FROM:				
import wood	82.0000	formula	x4	
non-agr. soil	422.0000	formula	x73	
==== Total =====	504.0000			
OUTPUTS OF wood industry TO:				
paper industry	118.0000	formula	x100	
furniture industry	227.0000	bal.item*	x101	
combustion processes	98.0000	formula	x102	
export wood	61.0000	formula	x103	
==== Total =====	504.0000			
INPUTS OF paper industry FROM:				
wood industry	118.0000	formula	x100	
==== Total =====	118.0000			
OUTPUTS OF paper industry TO:				
households	118.0000	bal.item*	x104	
==== Total =====	118.0000			
INPUTS OF furniture industry FROM:				
wood industry	227.0000	bal.item	x101	
==== Total =====	227.0000			
OUTPUTS OF furniture industry TO:				
households	227.0000	bal.item*	x105	
==== Total =====	227.0000			
INPUTS OF NH3 industry FROM:				
industrial N2 fixation	8697.9994	bal.item*	x5	
import other NH/NO products	1295.0000	formula	x7	
==== Total =====	9992.9994			
OUTPUTS OF NH3 industry TO:				
fertilizer industry	9439.0000	bal.item	x14	
households	32.0000	formula	x15	
export other NH/NO products	464.0000	formula	x16	
air	57.9994	formula	x17	
economic stock	0.0000	formula	x18	
==== Total =====	9992.9994			
INPUTS OF combustion processes FROM:				
import fossil fuels	962.0000	formula	x9	
recovery fossil fuels	0.0000	formula	x10	
NOx from N2	2246.0000	formula	x11	
wood industry	98.0000	formula	x102	
==== Total =====	3306.0000			
OUTPUTS OF combustion processes TO:				
export fossil fuels	0.0000	formula	x12	
air	3208.0000	formula	x13	
landfill	98.0000	bal.item*	x114	
==== Total =====	3306.0000			
INPUTS OF fertilizer industry FROM:				
import fertilizers	1541.0000	formula	x6	
NH3 industry	9439.0000	bal.item*	x14	
==== Total =====	10980.0000			
OUTPUTS OF fertilizer industry TO:				
crop/grass production	10495.0000	formula	x19	
export fertilizers	485.0000	formula	x20	
==== Total =====	10980.0000			

INPUTS OF animal production FROM:

fodder industry	3087.9865	formula	x21
crop/grass production	9370.1306	formula	x22
==== Total =====	12458.1171		

OUTPUTS OF animal production TO:

crop/grass production	10002.0952	bal.item*	x23
food industry	1685.0151	formula	X24
air	771.0067	formula	x25
==== Total =====	12458.1171		

INPUTS OF **crop/grass production** FROM:

fertilizer industry	10495.0000	formula	X19
animal production	10002.0952	bal.item	x23
sewage treatment	103.6500	formula	X55
waste treatment	50.4952	formula	X62
air	1311.7049	formula	X67
biological N2 fixation	300.0000	formula	X71
crop/grass production	1155.9735	formula	X98
==== Total =====	23418.9188		

OUTPUTS OF crop/grass production TO:

animal production	9370.1306	formula	x22
fodder industry	2013.0954	formula	x26
export agrprod for food	503.9599	formula	X27
food industry	1284.0218	formula	X28
economic stock	116.9984	formula	x29
denitrification in agr. soils	3602.5730	formula	x30
air	1535.4042	formula	X31
ground water	3602.5730	bal.item*	X32
surface water	234.1892	formula	x33
crop/grass production	1155.9735	formula	x98
==== Total =====	23418.9188		

INPUTS OF households FROM:

import agrprod for dir.cons.	55.0000	formula	X3
import other N products	0.0000	formula	X8
NH3 industry	32.0000	formula	xl5
food industry	2850.0000	formula	X34
economic stock	33.0000	formula	X41
paper industry	118.0000	bal.item	X104
furniture industry	227.0000	bal.item	X105
==== Total =====	3315.0000		

OUTPUTS OF households TO:

economic stock	302.0000	formula	X42
sewage treatment	1968.4600	formula	x43
waste treatment	1044.5400	bal.item*	x44
==== Total =====	3315.0000		

INPUTS OF sewage treatment FROM:				
	food industry	175.1518	formula	x37
	fodder industry	171.5548	formula	x39
	households	1968.4600	formula	x43
	==== Total =====	2315.1667		
OUTPUTS OF sewage treatment TO:				
	air	0.0000	formula	x52
	surface water	1805.8797	bal.item*	x53
	landfill	123.2595	formula	x54
	crop/grass production	103.6500	formula	x55
	disposal at sea	19.6095	formula	x56
	industrial denitrification	262.7680	formula	x57
	===== Total =====	2315.1667		
INPUTS OF waste treatment FROM:				
	households	1044.5400	bal.item	x44
	economic stock	302.0000	formula	x58
	==== Total =====	1346.5400		
OUTPUTS OF waste treatment TO:				
	landfill	1296.0447	bal.item*	x59
	air	0.0000	formula	x60
	immobilization	0.0000	formula	x6l
	crop/grass production	50.4952	formula	x62
	==== Total =====	1346.5400		
INPUTS OF economic stock FROM:				
	NH3 industry	0.0000	formula	xl8
	crop/grass production	116.9984	formula	x29
	households	302.0000	formula	x42
	==== Total =====	418.9984		
OUTPUTS OF economic stock TO:				
	households	33.0000	formula	x4l
	waste treatment	302.0000	formula	x58
	accumulation economy	83.9984	bal.item*	x63
	==== Total =====	418.9984		
INPUTS OF air FROM:				
	combustion processes	3208.0000	formula	xl3
	NH3 industry	57.9994	formula	x17
	animal production	771.0067	formula	x25
	crop/grass production	1535.4042	formula	x31
	sewage treatment	0.0000	formula	x52
	waste treatment	0.0000	formula	x60
	inflow air (NOx)	245.0000	formula	x64
	inflow air (NHx)	77.0000	formula	x65
	non-agr. soil	20.4500	formula	x74
	landfill	0.1957	formula	x117
	==== Total =====	5915.0560		
OUTPUTS OF air TO:				
	surface water	80.3085	formula	x66
	crop/grass production	1311.7049	formula	x67
	non-agr. soil	1285.2735	bal.item*	x68
	outflow air (NOx)	2250.8867	formula	x69
	outflow air (NHx)	555.6827	formula	x70
	north sea	431.1997	formula	x108
	===== Total =====	5915.0560		

INPUTS OF surface water FROM:

crop/grass production	234.1892	formula	x33
food industry	111.1514	formula	x38
fodder industry	108.5599	bal.item	x40
sewage treatment	1805.8797	bal.item	X53
air	80.3085	formula	X66
non-agr. soil	15.8527	formula	x75
inflow surface water	0.0000	formula	X82
ground water	0.0000	formula	X87
landfill	0.1517	formula	X118
===== Total =====	2356.0931		

OUTPUTS OF surface water TO:

aquatic sediment	961.1402	bal.item*	x84
outflow surface water	449.9848	formula	x85
natural denitrification	0.0000	formula	x86
north sea	944.9681	formula	X107
==== Total =====	2356.0931		

INPUTS OF non-agr. soil FROM:

air	1285.2735	bal.item	X68
biological N2 fixation	300.0000	formula	x72
==== Total =====	1585.2735		

OJTPUTS OF non-agr. soil TO:

wood industry	422.0000	formula	x73
air	20.4500	formula	x74
surface water	15.8527	formula	X75
ground water	545.3340	bal.item*	x76
natural denitrification	581.6368	formula	X79
==== Total =====	1585.2735		

INPUTS OF landfill FROM:

sewage treatment	123.2595	formula	X54
waste treatment	1296.0447	bal.item	X59
combustion processes	98.0000	bal.item	X114
==== Total =====	1517.3042		

OUTPUTS OF landfill TO:

accumulation environment	1502.1312	bal.item*	x95
air	0.1957	formula	X117
surface water	0.1517	formula	X118
ground water	3.4458	formula	X119
natural denitrification	11.3798	formula	X120
==== Total =====	1517.3042		

INPUTS OF ground water FROM:

crop/grass production	3602.5730	bal.item	X32
non-agr. soil	545.3340	bal.item	X76
landfill	3.4458	formula	X119
==== Total =====	4151.3528		

OUTPUTS OF ground water TO:

surface water	0.0000	formula	x87
environmental stock	4151.3528	bal.item*	x88
==== Total =====	4151.3528		

INPUTS OF aquatic sediment FROM:				
	surface water	961.1402	bal.item	x84
OUTPUTS OF aquatic sediment TO:				
	environmental stock	961.1402	bal.item*	x89
	natural denitrification	0.0000	formula	x94
	==== Total =====	961.1402		
INPUTS OF environmental stock FROM:				
	ground water	4151.3528	bal.item	x88
	aquatic sediment	961.1402	bal.item	x89
	===== Total =====	5112.4930		
OUTPUTS OF environmental stock TO:				
	accumulation environment	5112.4930	bal.item*	x97
	==== Total =====	5112.4930		
INPUTS OF north sea FROM:				
	inflow from ocean	4000.0000	formula	x106
	surface water	944.9681	formula	x107
	air	431.1997	formula	x108
	food industry	64.0005	formula	x115
	fodder industry	62.9949	formula	x116
	==== Total =====	5503.1631		
OUTPUTS OF north sea TO:				
	food industry	266.0000	formula	x109
	fodder industry	0.0000	formula	x110
	natural denitrification	769.0120	formula	x111
	outflow to ocean	3103.0686	formula	x112
	accumulation environment	1365.0825	bal.item*	x113
	==== Total =====	5503.1631		

1.1 Nitrogen chemicals production

Nodes

NH_3 and other N-chemicals production
fertilizer industry
(consumers)
(crop/grass production)
(environmental nodes)

Flows

x6 import fertilizers
x7 import NH/NO products
x16 export NH/NO products
x20 export fertilizers

* imports and exports of fertilizers and other nitrogen containing chemicals are from Eurostat trade statistics (chemical & allied industries) (Eurostat, 1990c Parts B and C). N content of fertilizer is based on the assumptions made by CBS when drawing up their N balances for the Netherlands (Olsthoorn, 1993). For the chemicals, the N content is based on the molecular composition of the chemical.

x5 industrial N fixation
x17 emissions air NH_3 industry
x14 ammonia to fertilizer industry
x19 fertilizers to agricultural production

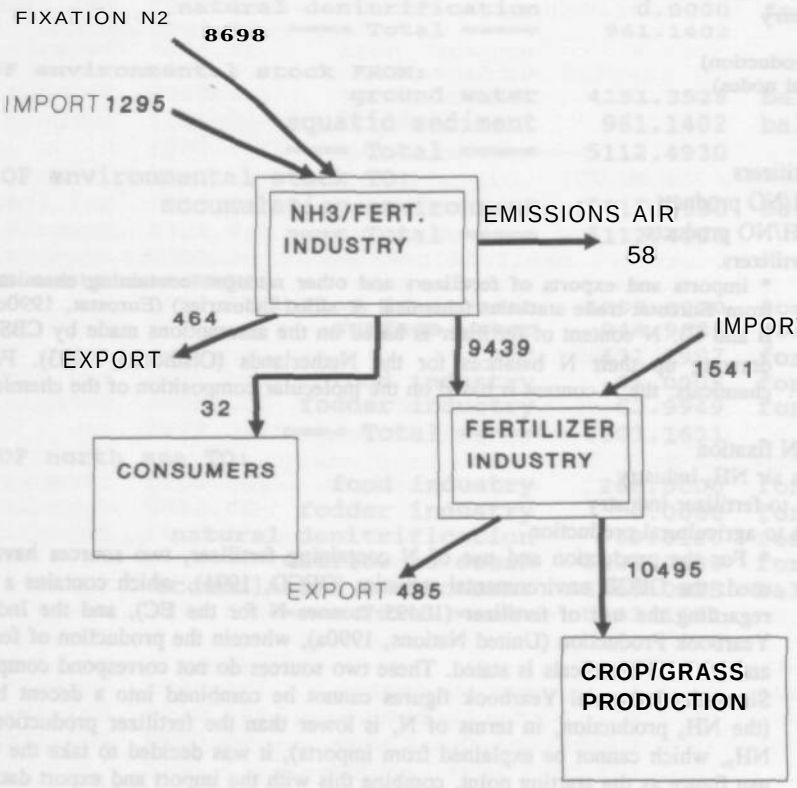
* For the production and use of N containing fertilizer, two sources have been used: the OECD environmental statistics (OECD, 1991), which contains a figure regarding the use of fertilizer (10495 ktonnes N for the EC), and the Industrial Yearbook Production (United Nations, 1990a), wherein the production of fertilizer and other N chemicals is stated. These two sources do not correspond completely. Since the Industrial Yearbook figures cannot be combined into a decent balance (the NH_3 production, in terms of N, is lower than the fertilizer production from NH_3, which cannot be explained from imports), it was decided to take the OECD use figure as the starting point, combine this with the import and export data from the Eurostat trade statistics, and the production figure was then derived from that as a balancing item. The NH_3 production that in its turn has been derived from this figure, is very close to the figure given by the Industrial Production Yearbook (1% higher). Finally, the industrial fixation has been derived from this value, incorporating, of course, imports and exports and the industrial emissions.

* the emission from the chemical industry has been derived by scaling up the figure of the Netherlands coming from the CBS N-balance (Olsthoorn, 1993).

x15 N chemicals (anilines) to consumers

* the only consumer application of N in chemical products of any significance is anilines. The production of anilines has been taken from the Industrual Yearbook Production (United Nations 1990a). The N content is based on the molecular composition: C_6H_5-NH_2.

Figure A3.1 Nitrogen chemicals production cluster



1.2 Agricultural production

Nodes
crop/grass production
stock raising
food production
fodder production
(fertilizer industry)
(consumers)
(sewage treatment)
(waste treatment)
(environmental nodes)

Flows
x19 fertilizers to agricultural production
* see cluster N chemicals production
xSS sewage sludge application in agriculture
x62 compost application in agriculture
* see cluster consumers and waste treatment
x67 atmospheric deposition on agricultural soil
* see environmental cluster
x71 biological N fixation in agricultural soil
* see environmental cluster

the agricultural flows
The flows relating to import, export, production and use of agricultural products are based on two types of data: data regarding the various agricultural products, and data regarding the nitrogen content in them. For the agricultural products, the very detailed and extensive Eurostat agricultural statistics have been the main source. The nitrogen content is directly related to the protein content of agricultural products, so that there was very detailed information on this, as well. Sources were the Veevoedertabel (Centraal Veevoederbureau, 1986) for grass and fodder crops, and the CBS (Central Bureau of Statistics, 1992) and Starink & Hakkenbrak (1991) for food products. These data therefore can be described as quite reliable, with a margin error of not more than a few percentage points. The only exception to this is the grass and fodder crop production (see under x22 and x29).

the agricultural balance sheets
For many crops and animal products, balance sheets are available from the EU statistical bureau, containing imports, exports, production, use, harvest losses, and stock changes (Eurostat, 1990b). These sheets have been used, and in some cases have been combined with each other in order to prevent double countings. These combined balances are presented in Table A3.1 and Figures A3.2 and A3.3. For products that are being used but are not, or are only rarely, produced within the EC area, the imports have been taken into account separately (Eurostat 1990c, Part A). Most of these refer to fodder stuffs, such as maize, manioc, fish flour, soy, palm pits, and other oleagenous seeds, cakes and shreds. Also, products such as bananas, peanuts, beans, maize starch and coffee have been included.

Table A3.1 Balances for some of the most important agricultural products. In ktonnes N, EC-12, 1988.

	meat	eggs	milk	milkpr	potat	wheat	ol.sd	oilca	veget	fru
import	37	12	7	6	1	134	496	649	7	8
production	978	103	606	513	134	2718	698	736	144	21
export	60	2	8	82	5	475	6	53	16	2
use	962	113	605	468	115	2265	1128	1332	122	25
stock change	-2	-	-	-31	+9	+80	+29	-	-1	-
harvest losses	-	-	-	-	6	33	32	-	14	3
N-content (g/kg)	32	21	5.4	var.	3.3	17.6	32	40	3.2	0.8

x1 import agricultural products for fodder
x2, x3 import agricultural products for food
x27, x36 export food products
x98 harvest losses
x24 animal products to food industry
x41 agr. products from stock to food industry

* all from balance sheets (Eurostat 1990b), with N contents from Central Bureau of Statistics (1992) and Centraal Veevoederbureau Nederland (1986)

x22 grass

* for grass production, a comparison of the grassland area and the estimated total grass production (Eurostat, 1990b) indicates, in some cases, obvious errors (Denmark, for example, would produce an average of 37 tonnes/ha of dry weight grass, and the Netherlands of 21 tonnes/ha). In these cases, the area has been taken as the starting point, and a production per hectare has been assumed. An average grass production of 5.3 tonnes per hectare for the EU as a whole has been calculated from this, and has been used in the bookkeeping and model calculations. The N content in grass was known for the Dutch situation from the CBS nitrogen balance (Olsthoorn, 1993). This figure, 37.7 g/kg, was felt a bit high for the EU as a whole. Arbitrarily, a 30 g/kg was used. Together, this has lead to a total grass production, expressed in terms of nitrogen, of somewhat over a 9000 ktonnes of N. The only way this figure can be checked is by the animal production balance. However, this balance also has a large and rather uncertain outflow: manure. The N in manure estimate (see under x23) amounts to a little bit more than 7000 ktonnes N, leaving a balance deficit of something less than 3000 ktonnes N. In view of the uncertainties of the manure figures, which are felt to be even larger than those of grass production, it has been decided to shift this balance deficit to the manure and not to change the grass production figure.

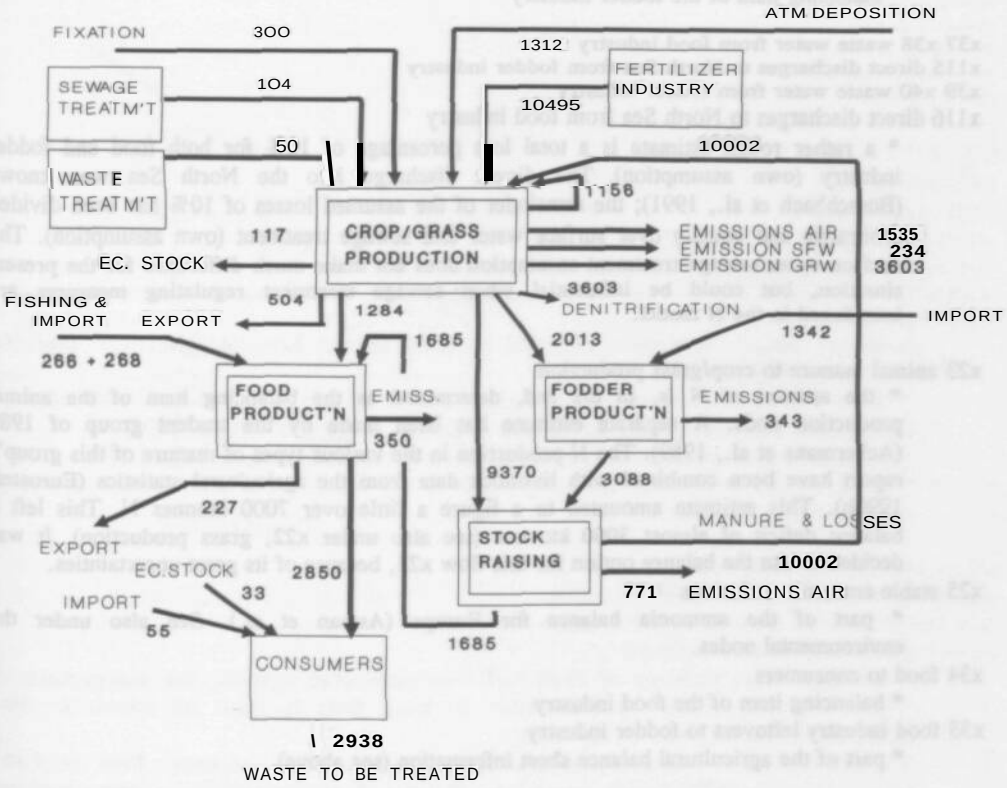
x26 crop to fodder industry
x28 crop to food industry

* in the agricultural balance sheets, a distinction has been drawn between use for humans, use for livestock, and industrial use (including a further production of food products).

x29 crop to stock

* green maize, perennial green fodder, clover, lucerne, and other cattle crops: of these crops, which usually go directly to livestock without interference of the fodder industry, a production area was available from the Eurostat agricultural statistics. The production per hectare in most cases appears to be rather wild guess, based on data form The Netherlands (Central Bureau of Statistics, 1992). This figure, therefore, is also highly uncertain.

Figure A3.2 Agricultural production cluster



x30 x31 x32 x33 losses from agricultural soils to the environment

* see under the environmental cluster

x21 fodder from fodder industry to stock raising

*** balancing item of the fodder industry**

x37 x38 waste water from food industry
xl 15 direct discharges to North Sea from fodder industry
x39 x40 waste water from fodder industry
x1 16 direct discharges to North Sea from food industry

* a rather rough estimate is a total loss percentage of 10% for both food and fodder industry (own assumption). The direct discharge into the North Sea was known (Busschbach et al., 1991); the remainder of the assumed losses of 10% has been divided arbitrarily and equally over surface water and sewage treatment (own assumption). The surface water/sewage treatment assumption does not make much difference for the present situation, but could be influential when sewage treatment regulating measures are introduced in the N model.

x23 animal manure to crop/grass production

* the amount of N is, in the end, determined as the balancing item of the animal production node. A separate estimate has been made by the student group of 1989 (Ackermans et al., 1989). The N-production in the various types of manure of this group's report have been combined with livestock data from the agricultural statistics (Eurostat, 1990b). This estimate amounted to a figure a little over 7000 ktonnes N. This left a balance deficit of almost 3000 ktonnes (see also under x22, grass production). It was decided to use the balance option for this flow x23, because of its great uncertainties.

x25 stable ammonia emissions

*** part of the ammonia balance for Europe (Asman et al.). See also under the environmental nodes.**

x34 food to consumers

* balancing item of the food industry

x35 food industry leftovers to fodder industry

* part of the agricultural balance sheet information (see above)

x109 fish from North Sea to food industry

* fishery statistics of Eurostat for the amounts (Eurostat, 1990c), Starink & Hakkenbrak for the N-content of fish.

1.3 Wood and fossil fuels

Nodes
wood industry
paper industry
furniture industry
combustion processes
(consumers)

Flows

x4 import wood
x103 export wood
x73 harvest wood
x100 wood to paper industry, x104 paper to consumers
x101 wood to furniture industry (and other wood applications), x105 furniture to consumers
xl02 wood to fireplaces

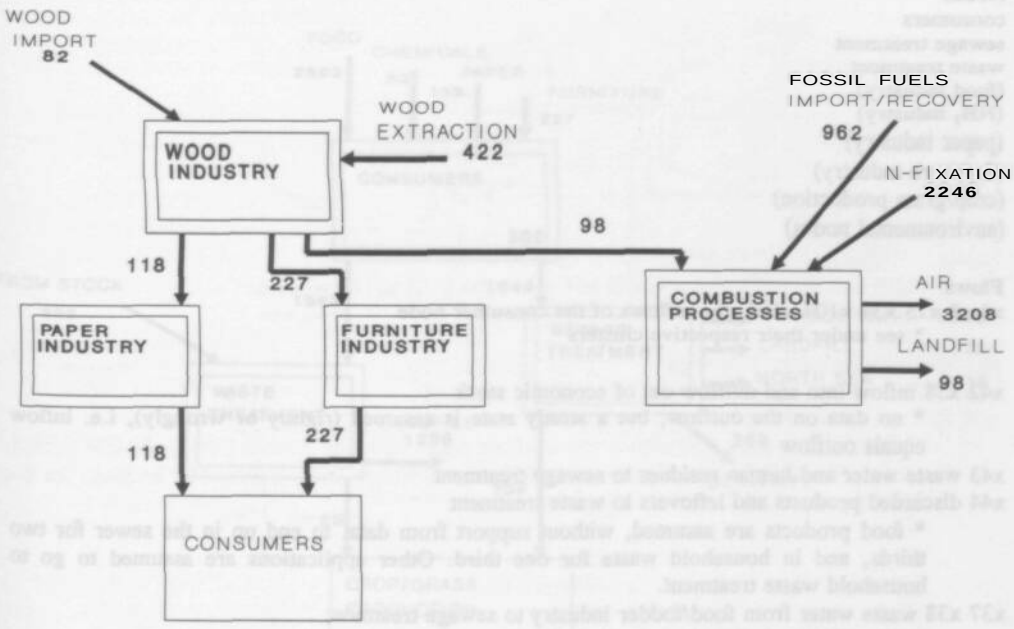
* import, export, production of wood in cubic metres: Eurostat agricultural statistics (Eurostat, 1990b)
* kg wood per cubic metre (0.7 kg/dm³), N-content in wood (0.55% wet weight): Schlesinger: biogeochemistry, an analysis of global change (Schlesinger, 1991).
* destination of wood to the various applications: World Resources Institute (1990)
* flows to the consumers: balancing items of the wood, paper and furniture industry nodes.

x9 import/recovery fossil fuels
x11 NO_x generation in combustion processes
x13 emissions to air combustion processes
x114 landfilled incineration residues

* the import and recovery of fossil fuels originates from Eurostat, the energy balance sheets (Eurostat, 1988). The N content in fossil fuels is based on figures for the Netherlands (Van der Voet et al., 1989).

The total amount of NO_x emissions from fossil fuel combustion was known from the N air balance (EMEP, 1989), which comes from the very detailed acidification inventarizations (see under the environmental cluster). By extracting the fraction that originates from N locked in coal, oil and gas, the remainder is assumed to be caused by NO_x formation out of atmospheric N_2. The landfilled incineration residues was added later, probably incorrectly, when the use of wood in fireplaces was included in the node "combustion processes". The inflow no longer matched the outflow, and thus landfill was added as a balancing item. In retrospect, it would probably have been better to decrease the NO« formation out of N_2, which was the balancing item to start with.

Figure A3.3 Wood and fossil fuels cluster



1.4 Consumers and waste treatment

Nodes
consumers
sewage treatment
waste treatment
(food industry)
(NH_3 industry)
(paper industry)
(furniture industry)
(crop/grass production)
(environmental nodes)

Flows
x3 x8 x15 x34 x104 x105, the inflows of the consumer node
* see under their respective clusters

x42 x58 inflow into and outflow out of economic stock
* no data on the outflow, but a steady state is assumed (rightly or wrongly), i.e. inflow equals outflow

x43 waste water and human residues to sewage treatment

x44 discarded products and leftovers to waste treatment
* food products are assumed, without support from data, to end up in the sewer for two thirds, and in household waste for one third. Other applications are assumed to go to household waste treatment.

x37 x38 waste water from food/fodder industry to sewage treatment
* see under agricultural production cluster

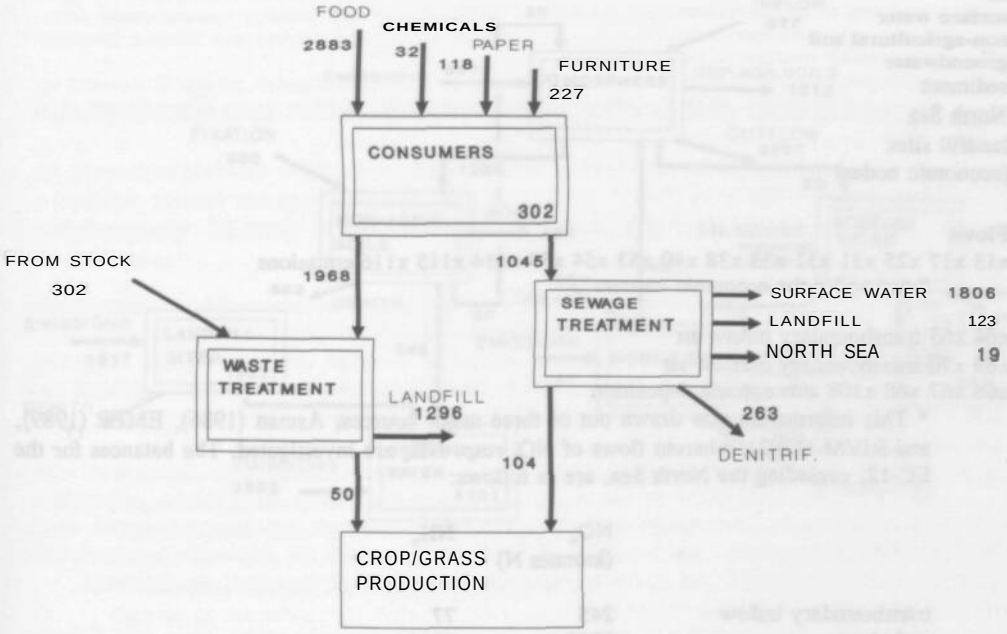
x54 x55 x56 destination of sewage sludge
* the relative destination has been taken from the sludge report of the UK Water Research Centre (1986) and applied to the amount of N ending up in sludge (280 ktonnes), also from this report.

x57 denitrification in sewage treatment plants
* calculated by : 16% of the effluent (UK Water Research Centre, 1986) is treated, with an effectiveness of 60% (own assumption).

x53 sewage treatment effluent
* balancing item of the sewage treatment balance

x59 x62 destination waste treatment residues
* compost: 5% of N in GF waste is recycled in compost (own assumption)
* the remainder, as a balancing item of the waste treatment node, is assumed to be landfilled. This is undoubtedly untrue, since a part of the N ends up in incinerators and consequently is emitted into the atmosphere. Again, this may be a part of the NO_x balance, and may lower the NO, formation out of N_2 figure. However, no information was available regarding the extent of the flow.

Figure A3.4 Consumers and waste treatment cluster



1.5 The environment

Nodes
air
surface water
non-agricultural soil
groundwater
sediment
North Sea
landfill sites
(economic nodes)

Flows
x13 x17 x25 x31 x32 x33 x38 x40 x53 x54 x59 x114 x115 x116 emissions
*** see under the economic clusters**

x64 x65 transboundary inflow air
x69 x70 transboundary outflow air
x66 x67 x68 x108 atmospheric deposition

* This information was drawn out of three major sources, Asman (1986), EMEP (1989), and RIVM (1992), wherein flows of NO_x resp. NH, are investigated. The balances for the EC-12, excluding the North Sea, are as follows:

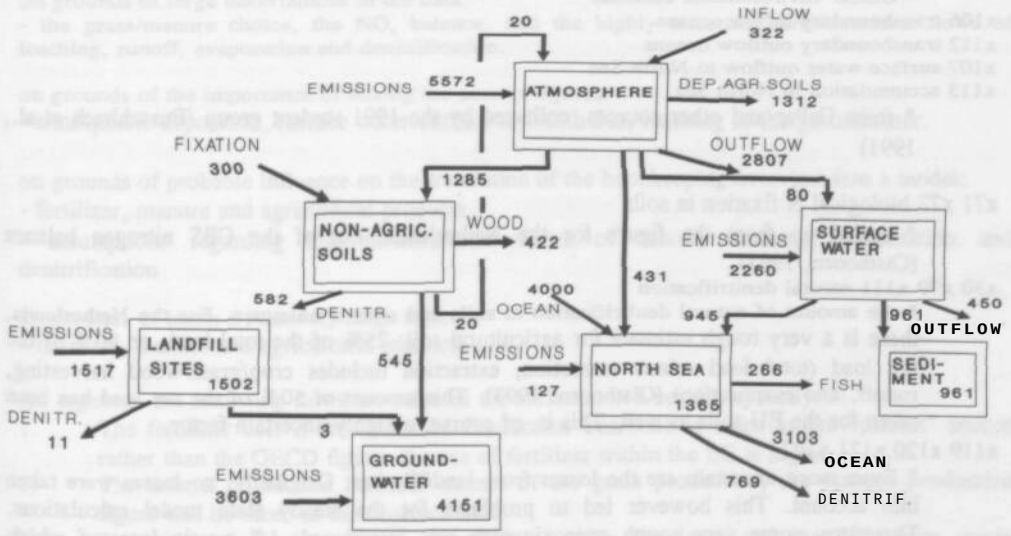
	NO_x (ktonnes N)	NH_x
transboundary inflow	245	77
emissions	3208	2395*
deposition	965	1719
transboundary outflow	2488*	753

* = balancing item.

The "emissions" figure for ammonia includes industrial emissions, stable emissions and evaporation from all types of soils. Therefore, this does not correspond in all cases with what is called emissions in this SFA. The stable emission is calculated by subtracting the industrial emissions and the evaporation (see below) from the total emissions of NH_x. The atmospheric deposition out of the balance is divided over agricultural soil (49%), non-agricultural soil (48%), and surface water (3%), according to the respective surfaces of these categories within the EU (Eurostat 1990a).
The transboundary outflow is corrected for the system extension to encompass the North Sea. The deposition of both NO_x and NH, on the North Sea was based on an estimate made in the Oslo & Paris Commission report: Monitoring and Assessment (OsPar, 1992). This deposition was subtracted from the transboundary outflow as it appears in the above balances. According to the report, the margins of error are considerable here (330 - 520 ktonnes of N).

x33 x75 runoff
* no data available, own assumption is 1 % of the soils load.
x84 sedimentation, x89 accumulation in sediment
* balancing item of surface water balance, own assumption is that all sedimented N

Figure A3.5 The environmental cluster



accumulates. This is in all probability not true, since denitrification processes are known to occur in sediments as well. The extent however is completely unknown.

x85 transboundary outflow surface water

* OECD environmental statistics

x106 transboundary inflow oceans
x112 transboundary outflow oceans
x107 surface water outflow to North Sea
x113 accumulation in North Sea

* from OsPar and other sources, collected by the 1991 student group (Busschbach et al., 1991)

x71 x72 biological N fixation in soils

* scaled up from the figure for the Netherlands, out of the CBS nitrogen balance (Olsthoorn, 1993).

x30 x79 x111 natural denitrification

* the amount of natural denitrification in soils and sites is unknown. For the Netherlands, there is a very rough estimate for agricultural soil: 25% of the total load, or 50% of the net load (total load minus extraction, extraction includes crop/grass/wood harvesting, runoff, and evaporation) (Olsthoorn, 1993). This amount of 50% of the net load has been taken for the EU soils as well. This is, of course, a highly uncertain factor.

x119 x120 x121 x122

* Even more uncertain are the losses from landfill sites. Originally, no losses were taken into account. This however led to problems for the steady state model calculations. Therefore, some very rough approximation was introduced: 1% yearly loss, of which 0.001% evaporation, 0.01% runoff, 0.225% leaching and the remainder denitrification (own assumptions). There could be major discrepancies from the actual situation here.

x31 x74 ammonia evaporation from soils

* no direct data available; calculated as a fraction of the total input. A different assumption has been made for animal manure and the other inflows. The assumption was 19% for manure and 1.9% for other inflows, based on Dutch figures from Van der Voet et al. (1989).

x32 x76 leaching, x88 accumulation groundwater

* balancing items of soils and groundwater balances.

1.6 Conclusions: data to be varied in a sensitivity analysis

Data to include in a sensitivity analysis are:
on grounds of large uncertainties in the data:
- the grass/manure choice, the NO_x balance, and the highly uncertain environmental flows of leaching, runoff, evaporation and denitrification.

on grounds of the importance of having the correct figures:
- atmospheric deposition, surface water outflow to North Sea, leaching to the groundwater.

on grounds of probable influence on the translation of the bookkeeping overview into a model:
- fertilizer, manure and agricultural products
- assumptions regarding the environmental flows of runoff, leaching, evaporation and denitrification

on grounds of being a relatively large figure
- fertilizer, manure and agricultural products

All together, the following flows are selected for variation in a sensitivity analysis:

1. The fertilizer use: if the Industrial Production Yearbook is taken as the "correct" source rather than the OECD figure, the use of fertilizer within the EC is higher.
2. The animal production balance: instead of the grass production, the manure production figure will be taken as the "correct" one.
3. The NO, balance: the flows regarding wood in fireplaces and the NO_x from waste incineration will be assumed as contributing to the overall emission of 3208 ktonnes of N. This will certainly imply a lower NO, formation on the one hand, and lower landfill figures on the other.
4. For the environmental flows of runoff, leaching, evaporation and denitrification, other assumptions will be made, in different combinations:
   - maximizing denitrification: 75% of the net soil load, which also can be made higher by lowering evaporation (10% of manure, 1% of other inflows) and runoff (0.1% instead of 1%)
   - maximizing the air load: an evaporation of 30% of manure and 3% of other soil inflows
   - maximizing the surface water load: a runoff of 5% instead of 1 %, also of landfill sites
   - maximizing the groundwater load: lowering the denitrification rate to 25% of the net load, changes in evaporation and runoff as under maximizing denitrification.

1.7 Results of the sensitivity analysis

1.7.1 Fertilizer

In Table A3.2, the results of changed assumptions regarding production and use of fertilizer on the agricultural and environmental flows are presented. Imports and exports are not changed. NITROG contains flows out of the original overview, NITROG2 is the changed one.

Table A3.2 Changes in N-flows as a result of higher production and use of industrial fertilizer

Assumed regime	NITROG	NITROG2
	Amount (ktonnes N/y)	
Flow		
Agricultural soil		
Inflow	23421	24042
Harvest	14444	14444
Animal manure	10001	10015
Losses	8977	9597
Air		
Total inflow	5925	5925
Surface water		
Inflow	2323	2329
Sedimentation	928	934
Groundwater		
Accumulation	4147	4448
Non-agricultural soil		
Atmospheric deposition	1289	1289
North Sea		
Inflow (minus ocean)	1503	1503
Accumulation	1365	1365
Denitrification		
sewage treatment	263	263
agricultural soil	3601	3901
non-agr. soil	584	584
North Sea	769	769

By adopting the Industrial Yearbook Fertilizer as the "correct" source, the amount of fertilizer used within the EU appears somewhat higher. Since the harvest is not influenced, the main difference from the original file lies in the losses from agricultural soil. This leads to somewhat higher denitrification and somewhat higher leaching to groundwater. The other environmental and agricultural flows are not influenced.

1.7.2 The animal production balance

In Table A3.3, the results of taking the manure bookkeeping data as the reliable source instead of the grass production data are presented. NITROG3 is the changed file.

Table A3.3 Changes in N-flows as a result of a lower amount of N in manure

Assumed regime	NITROG	NITROG3
	Amount (ktonnes N/y)	
Flow		
Agricultural soil		
Inflow	23421	20653
Harvest	14444	12044
Animal manure	10001	7233
Losses	8977	8609
Air		
Total inflow	5925	5925
Surface water		
Inflow	2323	2295
Sedimentation	928	900
Groundwater		
Accumulation	4147	4161
Non-agricultural soil		
Atmospheric deposition	1289	1289
North Sea		
Inflow (minus ocean)	1503	1503
Accumulation	1365	1365
Denitrification		
sewage treatment	263	263
agricultural soil	3601	3615
non-agr. soil	584	584
North Sea	769	769

The crop/grass production balance appears to be the only one that is affected. A lower grass production on the output side is matched by a lower manure application on the input side. This means, that the environmental flows are barely affected. The only change that is more than trivial appears in the groundwater accumulation, which is somewhat lower than with the original assumptions.

1.7.3 The NO_x balance

NITROG4 contains the changed assumptions regarding the NO, formation. Table A3.4 shows the results.

Table A3.4 Changes in N-flows as a result of other assumptions regarding the NO_x formation

Assumed regime	NITROG	NITROG4
	Amount (ktonnes N/y)	
Flow		
Agricultural soil		
Inflow	23421	23421
Harvest	14444	14444
Animal manure	10001	10001
Losses	8977	8977
Air		
Total inflow	5925	5925
Surface water		
Inflow	2323	2323
Sedimentation	928	928
Groundwater		
Accumulation	4147	4147
Non-agricultural soil		
Atmospheric deposition	1289	1289
North Sea		
Inflow (minus ocean)	1503	1503
Accumulation	1365	1365
Denitrification		
sewage treatment	263	263
agricultural soil	3601	3601
non-agr. soil	584	584
North Sea	769	769

The two files are identical with regard to the agricultural and environmental flows. The significantly lowered NO, formation only results in a lower landfill.

1.7.4 The environmental flows

NITROG51 is the result of maximizing the denitrification, as described in 1.6. In NITROG52 the air load is maximized, in NITROG53 the surface water load. NITROG54, finally, aims at maximizing the groundwater load.

Table A3.5 Changes in N-flows as a result of various modifications in the environmental flows

Assumed regime	NITROG	NITROG51	NITROG52	NITROG53	NITROG54
		Amount (ktonnes N/y)			
Flow					
Agricultural soil					
Inflow	23421	22618	24548	23421	22618
Harvest	14444	14444	14444	14444	14444
Animal manure	10001	9198	11128	10001	9198
Losses	8977	8173	10102	8977	8173
Air					
Total inflow	5925	5925	5925	5925	5925
Surface water					
Inflow	2323	2097	2334	3291	2097
Sedimentation	928	702	939	1896	702
Groundwater					
Accumulation	4147	2129	4135	3722	6414
Non-agricultural soil					
Atm. deposition	1289	1289	1289	1289	1289
North Sea					
Inflow (min. ocean)	1503	1503	1503	1503	1503
Accumulation	1365	1365	1365	1365	1365
Denitrification					
sewage treatment	263	263	263	263	263
agricultural soil	3601	5551	3602	3133	1850
non-agr. soil	584	876	584	584	292
North Sea	769	769	769	769	769

The most striking result is that the total air load appears identical in each file. This is the result of the fact that the air balance is made up of data regarding the NO_x and NH_x balance. A higher figure for evaporation thus results not in a higher air load, but in a lower stable emission figure. This is shown most clearly in the NITROG52 file, wherein the evaporation is increased with a factor 1.5: the stable emission even becomes negative. This means, of course, that the balancing item of the animal production node increases: the manure production. The increased losses from agricultural soil disappear as extra evaporation, the other environmental flows are barely influenced.

The NITROG51 and NITROG54 file show a great similarity. The only difference is the destination of the agricultural soil losses: in NITROG51, it is the denitrification that is increased, in NITROG54 the leaching to the groundwater.

In NITROG53 we can see a shifting between runoff on the one hand, and denitrification and leaching on the other. The agricultural balances are not affected.

1.8 Conclusions

The main conclusion that can be drawn from the sensitivity analysis is that the assumptions tested regarding the changes in economic flows only appear to have minor impacts on the environmental flows. The changes tested in the environmental flows have all led to the expected results and did not influence others. The number of dependencies, loops and shifts via balancing items is apparently small, much less than in the case of cadmium. The bookkeeping overview for nitrogen therefore can be concluded to be rather robust, even more so than in the case of cadmium.

2 Nitrogen model

A number of the smaller imports and exports are fixed variables. Within the system, two variables have been given a fixed value: the food consumption on the one hand, and the fertilizer application on the other. It has been decided not to make the fertilizer application directly dependent on the food consumption level, by appointing the supply flows as balancing items, in order to keep open possibilities for introducing policy measures regarding the fertilizer use. The choice for balancing items is constructed in such a way that the supply flow from the food industry to consumers is the balancing item of the food consumption node, and that any disconnections between the supply of the food industry and agricultural products from within the EU is compensated by imports.

Since the choice for fixed variables and for balancing items is supported by solid argument, there seems no reason to vary this in a sensitivity analysis. The same is true for using the steady state situation as a basis for comparison: with cadmium, the model did not refer to the steady state, but with nitrogen it did.

The only relevant values to vary therefore are the distribution coefficients. In Section 1, the environmental flows appear to be highly uncertain and depend on rough assumptions. For the bookkeeping overview, however, mistakes in one assumption did not filter through to other flows. In a nitrogen model, this could be otherwise. The same applies for the agricultural flows. In this section, therefore, changes in distribution coefficients are introduced in ITROG3, which is the file containing the steady state situation belonging to the 1988 regime. The influence of these changes on the steady state outcome will be evaluated, as will the influence of these changes on the results of the calculations regarding the impacts of regime changes as made for the nitrogen case study. The uptake efficiency of crop, especially regarding manure, is selected as the most relevant coefficient to be varied (higher and lower).

The uptake efficiency of industrial fertilizer and manure is changed. In ITROG2a, the uptake coefficient for industrial fertilizer is lowered from 80% to 70%. In order to obtain an overview that is identical to ITROG2, which is based on the bookkeeping overview, the uptake coefficient for manure must be increased from 38% to 52%. In ITROG2b, the uptake coefficient for industrial fertilizer is raised from 80% to 90%, and the uptake coefficient for manure is accordingly lowered from 38% to 26%. This appears to be about the limit; a higher or lower coefficient seems rather farfetched.

ITROG2a and ITROG2b result in overviews identical to ITROG2. The long term steady state belonging to the ITROG2 regime is ITROG3. The differences with ITROG2 are small, because the agricultural N cycle, which constitutes the main part of the N chain, has a turnover rate of one year. ITROG3a and b, the steady states of ITROG2a and b, are identical to ITROG3, probably because only agricultural coefficients are changed, and the agricultural flows of the steady state and the present situation do not differ.

Table A3.6 The influence of changing the agricultural distribution coefficients

Assumed regime	ITROG2,2a,2b	ITROG3, 3a, 3b
	Amount (ktonnes N/y)	
Flow		
Agricultural soil		
Inflow	**23419**	**23419**
Harvest	**14444**	**14444**
Animal manure	10002	10002
Losses	8975	8975
Air		
Total inflow	5915	5935
Surface water		
Inflow	2356	2371
Sedimentation	961	976
Groundwater		
Accumulation	4145	4502
Non-agricultural soil		
Atmospheric deposition	1285	1305
North Sea		
Inflow (minus ocean)	1503	1503
Accumulation	1365	-
Stock	-	7443
Denitrification		
sewage treatment	263	263
agricultural soil	3603	3603
non-agr. soil	582	591
North Sea	769	1040

That the steady state situations of ITROG3, 3a and 3b are identical, does not mean that these files will also show identical reactions to regime changes. This is tested for three changes:

- the complete termination of the use of industrial fertilizer in ITROG31, 31a and 31b
- the complete abolishment of stock breeding in ITROG32, 32a and 32b
- the technical package, including sewage treatment, air emission reduction, central manure treatment for 25% of the produced manure, and "clean" application of manure in 10% of the EU agricultural area, in ITROG33, 33a and 33b.

In the table below, the results of ending the use of industrial fertilizer are presented.

Table A3.7 Changes in N-flows as a result of terminating the use of industrial fertilizer

Assumed regime	ITROG3	ITROG31	ITROG31a	ITROG31b
	Amount (ktonnes N/y)			
Flow				
Agricultural soil				
Inflow	23419	3330	3527	3170
Harvest	14444	1767	2030	1556
Animal manure	10002	2085	2248	1953
Losses	8975	1662	1496	1614
Air				
Total inflow	5935	4018	4053	3989
Surface water				
Inflow	2371	1818	1827	1810
Sedimentation	976	750	754	747
Groundwater				
Accumulation	4502	1206	1167	1238
Non-agricultural soil				
Atm. deposition	1305	665	677	655
North Sea				
Inflow (minus ocean)	1503	1051	1060	1045
Stock	7443	6801	6813	6792
Denitrification				
sewage treatment	263	242	243	242
agricultural soil	3603	615	570	651
non-agr. soil	591	271	277	267
North Sea	1040	950	952	949

The files' reactions to terminating the use of industrial fertilizer are not identical. However, when compared to the basic file ITROG3, the differences are relatively small. The conclusion that the main part of the EU's food must be imported still stands; the reduction in the level of crop/grass production varies from 87% in ITROG31a to 89% in ITROG31b. The differences are even smaller that might be expected beforehand, since the uptake efficiency of manure (the only fertilizer left, apart from atmospheric deposition and the small items of compost and sewage sludge) is reduced by more than 30%.

A similar difference, but the other way around, can be expected from the closing down of the entire stock breeding sector. Now, the ITROG32b, with the more efficient uptake of industrial fertilizer, will have the highest crop/grass production and the lowest losses from agricultural soil.

Table A3.8 Changes in N-flows as a result of terminating stock breeding

Assumed regime	ITROG3	ITROG32	ITROG32a	ITROG32b
	Amount (ktonnes N/y)			
Flow				
Agricultural soil				
Inflow	23419	4164	4130	4197
Harvest	14444	3290	2889	3688
Animal manure	10002	0	0	0
Losses	8975	875	1238	510
Air				
Total inflow	5935	738	738	739
Surface water				
Inflow	2371	1880	1852	1908
Sedimentation	976	781	769	792
Groundwater				
Inflow	4502	934	1117	752
Non-agricultural soil				
Atm. deposition	1305	154	154	154
North Sea				
Inflow (minus ocean)	1503	794	783	806
Stock	7443	6436	6420	6452
Denitrification				
sewage treatment	263	262	259	266
agricultural soil	3603	388	570	205
non-agr. soil	591	16	16	16
North Sea	1040	899	897	902

Again, there are differences in reaction. These however are minor compared to the differences with the original ITROG3. The reduction in crop/grass production varies from 75% in ITROG32b to 80% in ITROG32a. The same variation can be detected for the inflow of nitrates into the groundwater. For the other environmental flows, the relative differences are even smaller.

The technical measure package may prove to be the most sensitive one. The conclusion here is, as stated in Chapter 8, that the technical package solves two out of three problems, the North Sea and the atmospheric deposition. The third problem, the leaching of nitrates to the groundwater, does not appear to be solved. A decrease of 15% seems inadequate. It is possible that changes in distribution coefficients may increase this 15% significantly. ITROG3 once again represents the steady state model used in the case study, ITROG33 the steady state model with the technical measures, and ITROG33a and ITROG33b the models with the changed assumptions regarding uptake efficiency under the technical measure-regime. In addition, a file ITROG33c is defined. In this file, the uptake efficiencies are modified once again with the aim to establish the point where the conclusions of the case study no longer seem justified. In ITROG33a and ITROG33b the uptake efficiency is altered and the outcome is evaluated. In ITROG33c the desired outcome is used to determine the required change in uptake efficiency: what efficiency is needed in order to reduce the flow to the groundwater with 50%, combined with a steady agricultural production? The table below shows the results.

Table A3.9 Changes in N-flows as a result of technical measures

Assumed regime	ITROG3	ITROG33	ITROG33a	ITROG33b	ITROG33c
		Amount (ktonnes N/y)			
Flow					
Agriculturalsoil					
Inflow	23419	22391	22867	22022	18188
Harvest	14444	14444	14444	14444	14444
Manure	10002	8022	8022	8022	8022
Treated man.	-	2407	2407	2407	2407
Losses	8975	7948	8423	7579	5781
Air					
Total inflow	5935	1978	1985	1973	1918
Surface water					
Inflow	2371	1221	1226	1217	1178
Sedimentation	976	512	514	511	220
Groundwater					
Accumulation	4502	4030	4263	3849	2100
Non-agricultural soil					
Atm. depos.	1305	586	588	584	566
North Sea					
Inflow - ocean	1503	626	628	624	602
Stock	7443	61%	6200	6194	6165
Denitrification					
sew. treatm.	263	1662	1662	1662	1662
agric. soil	3603	3270	3502	3090	1350
non-agr. soil	591	232	233	231	222
North Sea	1040	866	866	865	861

Again, the differences between ITROG33, 33a and 33b are small. The groundwater load is somewhat lower for ITROG33b, with the highest uptake efficiency for industrial fertilizer. This variation of the agricultural distribution coefficients does not lead to different conclusions as those °f Chapter 8. As for ITROG33c, it appears that in order to attain a 50% reduction of the flow to the groundwater, the uptake efficiency of all fertilizers (industrial fertilizer as well as manure, compast and sludge) must *increase to 80%*. Without central manure treatment this does not seem a realistic assumption. An alternative, namely a full denitrification of manure and replacement by

fertilizer, is also unrealistic since this also involves central manure treatment for the bulk of the produced manure.

The conclusions of Chapter 8 therefore seem rather robust. However, the 80% uptake efficiency is not theoretically impossible. In such a case, the assumptions of the model must be reviewed with some more care. We have to consider the differences between the various soil types: if agriculture would be shifted, for a considerable part, from sand to clay and peat, the outcome may be different since losses to the groundwater mainly occur on sandy soils. We also have to consider the assumption of linearity in the model: at low fertilizer application levels, the uptake efficiency may be considerably higher than at high levels. We then must look into the variation of application levels within the EU and aim at cutting down surpluses locally. On the other hand, the high level application areas hardly correspond with the areas where the problems actually occur. A further breaking down of the EU regarding type of soil, type of crop and level of N-application is required in order to find out if a durable 80% uptake efficiency could theoretically be reached in combination with the current agricultural production. This would seem a gigantic task, which will not be undertaken within the framework of this thesis. For now, the conclusion that the current agricultural production is incompatible with the absence of nitrate pollution of the groundwater seems justified.

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