EC Programme Environment and Climate 1994-1998 ENV4_CT96_0230

April 1998 Final Report

EC ENVIRONMENTAL RESEARCH PROGRAMME

Research Area III - Economic and Social Aspects of the Environment

Summary Report

Materials Accounting as a Tool for Decision Making in Environmental Policy

(MAc TEmPo)

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EC Environment and Climate Research Programme (1994-1998) Research Theme 4 Human Dimension of Environmental Change

Summary Final Report

Contract n°: **ENV4-CT96-0230**

Title: **Materials Accounting as a Tool for Decision Making in Environmental Policy (MAc TEmPo)**

Key words: resource management, materials accounting, material flow analysis, material stock, policy decisions, environmental management, sustainable development, urban metabolism

Reporting period: 1/5/96 - 30/4/98 (full period)

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PART A: SUMMARY REPORT

Part A „Summary Report" outlines the main objectives, approaches and results of the five MAc TEmPo teams. Parts B1 to B5 are short versions of the individual research work. In addition, the teams have produced full reports of their work, which are available from the authors (see partners addresses).

I Objectives

Regions have a metabolism like a biological organism or an ecosystem. Sustainable development implies among other things, that this metabolism is directed towards optimum use and conservation of available resources, and long-term environmental protection. Hence, methods are needed to analyse, evaluate and control this regional metabolism.

Materials accounting comprises the analysis of flows and stocks of materials ("Material Flow Analysis MFA") in a given region in a systematic, rigid and comparable way. MFA is a complementary tool to traditional environmental and resource management approaches. It provides the necessary links between anthropogenic activities and their impacts on the environment. MFA is based on a holistic approach. It examines the total material flow into a given system such as a private household, company, city, region etc., the stocks and flows within this system, and the resulting outputs from the system to other regions and to the environment.

The five partners engaged in MAc TEmPo decided to share and expand their individual experience in materials accounting in order to:

- improve the MFA methodology,
- apply MFA methods in the field of sustainable development, namely resource conservation and environmental protection in highly urbanised areas,
- investigate the use of MFA as a base for policy decisions regarding anthropogenic metabolism.

The main objective of MAc TEmPo was to supply tools for decision makers in environmental protection and resources conservation. Previous work of the partners indicated, that MFA can be successfully used for: Early recognition of future problems of environmental loadings and resource depletion, to set priorities and to define measures for efficient environmental protection and resources utilization, and to analyse and improve the effect of measures taken in environmental policy. Based on this experience, MFA can be seen as a key instrument for the transition from today's "filter-strategy" to the next generation of source oriented environmental measures, focusing on *the total regional metabolism and not on wastes and emissions alone*.

Additional objectives were: to develop and improve existing and new computer based models for MFA, to share MFA experiences by the partners in four workshops and by the exchange of personnel, and to increase the number of experts in the field of MFA by involving additional research groups in the project. Also, the capacity to use statistics in support of environmental policy was to be improved. A more specific project aim was to look into early recognition of future risks of certain material flows by identifying long-term accumulations and depletion. *Measurable objectives* include the goals reached in the case studies (national and urban metabolism of metals, chlorine and other materials; MFA models) and to give first proposals of how to use MFA for decision making in environmental protection and resource conservation. In relation to this task, it should be noted, that the MAc TEmPo team included only one expert from the field of political science.

II Methodology

In order to reach the above mentioned objectives, an *empirical* research approach was taken. Original research work was carried out in the following three areas:

1. case studies of material flows on various levels
2. development and improvement of models to describe regional material balances
3. initial investigations into the use of MFA in the policy decision making process

In addition, four workshops were held to co-ordinate, discuss and evaluate MFA case studies and modelling approaches, to share and unify the methodology, and to derive common results concerning tools for decision making in environmental policy.

The four case studies selected for this project, which are summarised in Table II.1, were carried out in four different countries at various levels (local, regional, national, European). The main reason to establish four different case studies was to learn more about the anthropogenic metabolism and the means to control it, and to find similarities/differences in the metabolic behaviour of different anthropogenic systems. All case studies focused on urbanised areas, investigated the *total* flow of the substances selected and included transboundary and sometimes hinterland problems. Three of the case studies were mainly oriented towards substances (iron, zinc, carbon, chlorine etc.), and the other one was oriented more towards goods (biomass, water) and functions (construction). The case studies covered a wide array of specific regional metabolic systems: two studies dealt with the urban metabolism, one with both national and European substance flows and stocks, and one with a region including both urban and rural (agricultural) issues. Since the research questions and methods/models of the individual groups were complementary, general conclusions could be drawn from the individual results and applications.

The case studies focused on materials for which it was anticipated that data was comparatively easily available (metals), and on others such as carbon and chlorine which are more tedious to assess because of their very many different organic compounds. The materials investigated included those which are not in the public debate (iron), not yet in the debate (zinc) and those already in the centre of controversies (chlorine). This spectrum was relevant to the derivation of policy related conclusions.

Table II.1: Comparison of MAc TEmPo members and their case studies

Topic	Scale Spatial	 Temporal	Materials	Method of Investigation	Policy Link
Metabolism of Vienna (Massgoods, C, N, Metals)	Urban region - city of Vienna	1 year	Carbon, Nitrogen, Iron, Aluminium, Zinc, Lead	Analysis and comparison of flows and stocks with respect to the ratio of anthropogenic and geogenic	City of Vienna - Planning and Environment Department
Metal metabolism of Stockholm	Urban region - city of Stockholm	95 years	Cadmium, Chromium, Copper, Lead, Mercury, Nickel Zinc	Historical reconstruction and modelling of material flow and stock analysis, sediment cores	Local Environment Government in Stockholm, Swedish Environmental Protection Agency
Chlorine flows in Europe and European countries	European and national	lifespan of product	Chlorine, chlorinated compounds, mainly organic	Analysis, evaluation and modelling of material flow and stocks	Dutch Ministry of the Environment, European Union
Development of models, policy simulation		-		origin and control analysis for modelling of material flows and stocks	
Material balances for a Swiss Lowland region	Region - Swiss Lowland Synoikos	two generations (approx. 60 years)	Water, biomass, construction materials	Analysis and modelling of material flows and stocks, economic modelling, scenario development for resource use	21 Municipalities and 2 Cantons

In the MAc TEmPo case studies, several examples for static and dynamic models for materials management were presented. Based on existing material accounting methods, a new modelling approach was developed which incorporated the noise structure of the data. The objective was to exploit the potential of systems identification to improve MFA.

An attempt was made in the case studies to evaluate the use of materials accounting to support policy decisions. A comprehensive, social science investigation into this topic was not attempted because most of the Mac TEmPo team consisted of natural scientists and engineers. Hence, the conclusions presented here were drawn mainly from a technicians perspective.

The four *workshops* held in each participating country were instrumental for the exchange of information about methods, data, modelling and results. The workshops served as valuable platforms to present the case studies and to facilitate feedback discussions. While the early workshops were more dedicated to the case studies, the last two workshops focused primarily on policy related issues.

Four *National Advisory Boards* (Austrian, Dutch, Swedish, Swiss) consisting of both policy makers and scientists were established to provide the linkage between the project research activities and environmental policy. Their feedback was incorporated into the project in each phase.

Research personnel were exchanged for short term periods in order to enhance the exchange of expertise concerning methods, data acquisition and data treatment. This exchange also stimulated discussion and resolution of specific questions relating to the metal metabolism of urban regions.

III Main Results

The results fell into two main categories: those related to methodology developments and those related to material accounting case studies.

III.1 Methodology Developments

MFA Methodology : The objective of materials management is to firstly analyse, secondly to evaluate and thirdly to control material flows in view of certain goals such as sustainable development. The MAc TEmPo case studies confirmed, that MFA is an excellent tool for the first objective and is well suited to generate a base for the other two objectives. In itself, MFA does not allow to evaluate or control materials flows; additional methodologies, such as toxicology, environmental impact assessment (EIA), the concepts of Material Intensity Per unit Service (MIPS) or ecological footprints techniques (Sustainable Process Index SPI) are necessary for evaluation. Within MAc TEmPo, methods for these steps have not been explicitly discussed. However, each group has used its own criteria for evaluation and control of the flows and stocks. For example, the concept of "regional self sufficiency" was used in the case of the SYNOIKOS study. Just by analysing the material regime of a region, important characteristics of the regional metabolism can become apparent. A striking example is the strong accumulation of materials in urban anthropospheres, which was observed in all case studies. This finding implies significant consequences for future environmental protection and resource utilisation (see Materials Accounting Studies).

The methodology used in each case study was not identical. It appeared, that a certain minimum in standardisation was necessary for a mutual understanding of the systems investigated. In each case study a system was used comprising of a system boundary in time and space, of processes (transports, transformations and stocks), and of flows of goods and substances. It was agreed to apply the term "substance" as defined in chemistry (a substance is an entity of identical atoms or molecules, that is an element or a defined chemical compound), and to use the term "good" for matter (substances as well as mixtures of substances) with a positive or negative economic value such as construction materials or wastes. The term "material" comprises both substances and goods. In addition to this minimum set of definitions, each group used its own terms according to their needs, such as „Hibernation" for materials not in use, or „Hinterland" to show the dependency on neighbouring systems etc. The work of the MAc TEmPo team confirmed that the methodology for materials accounting can be applied on all levels and scales, such as households, cities, regions, and nations. For future studies and research in the field of materials accounting, it is recommended to follow this common set of definitions and to gradually enlarge it by a consensus process before establishing normalised standards.

Data Collection: To date, there exist no standardised methods or databases which allow simple, routine collection of data about flows and stocks of goods and substances. Thus, information needed for MFA was measured/assessed on an individual basis. It appeared that the necessary statistical data to establish balances for mass goods is available in all countries. Regionalised information is more difficult to obtain, and information about the flows and stocks of specific substances in general is not readily available from official statistical sources. In general, statistics focus on goods with an economical value. Substances, which are often hidden in goods, are rarely assessed. A main drawback of present data collection is, that the requirements of MFA are not yet taken into account, that is, that the information which is collected about the use of substances on one level (e.g. mining) is not yet linked to the next levels (production, trade, consumption, waste management, emissions).

A systematic development of an accounting system for selected substances could greatly facilitate the use of MFA and hence improve efficient materials management. A sound methodological approach over the full range of scales (households to countries), such as a national materials accounting system, could finally yield a comprehensive data set for many substances. Before official statistics are engaged in such data collection, it is important to define the exact goals, and to agree on the purpose as well as on the methodology of data collection and use.

Within the MAc TEmPo case studies, it was indispensable to engage experts with a profound knowledge of the method of MFA and of data about the flows and stocks of substances in anthropogenic systems. The main challenges in applying MFA involve establishing an appropriate material management system and selecting the critical data from all levels, including public and private sources covering production, supply, consumption and waste management.

The substance flows of different MAc TEmPo case study regions proved to be often quite similar. Nevertheless, some figures determined by the teams showed considerable deviations. The question remains open, as to whether these variations are due to data collection and treatment factors, or if they are a result of real differences between the anthropogenic metabolism of regions.

Modelling: All case studies presented have a common basis with respect to the physical principles applied, namely the laws of conservation of energy and matter. The first important and most creative step in each project is the choice of a combination of processes or subsystems, for which specific material and energy accounts have to be determined. The defined material management system can be described by a mathematical model. These mathematical models are used to understand the functioning of the whole system.

Models are based either on *a priori* assumptions or on the determination of unknown model parameters by available measurements. In the first approach, error propagation for a given system is calculated. The latter approach is a system identification approach. Both have been successfully applied in case studies. In the system identification approach the following problems have been solved: data reconciliation based on the precision of the measurements available, estimation of unmeasured flows, estimation of the model parameters corresponding to the subsystems, origins analysis and policy simulation (control analysis)

There are several software packages that are available to handle MFA (e.g. SFINX, SIMBOX). Within MAC TEmPo, each team has developed their own computer aided tools for calculating and visualising serving their specific purpose. However, in each case the methodological basis of SFA was the same (similar physical concepts). Eventually the best software should be selected by market mechanisms (user demands).

III.2 Materials Accounting Case Studies

Main messages: MFA of urban regions revealed two typical characteristics of the anthropogenic metabolism:

- The flow of most mass goods through urban areas is, compared to geogenic flows, large and predominantly linear (few cycles).
- The stocks of goods and substances in urban regions are large and increasing.

These observations are important for both future environmental protection and resource utilisation. During relatively short consumption phases, large amounts of materials are being accumulated in the infrastructure and in households. In one respect, these materials are valuable resources and can be used for reconstruction of the anthroposphere. This holds true if information about its concentrations and locations are available, and if the substances can be viably collected and recovered economically. For many substances used today, these prerequisites are not fulfilled yet. In contrast, large stocks of materials which are no longer in use ("Hibernating materials") may pose a future threat to the environment a long time after they have entered the market. The MAc TEmPo case studies have shown, that the amount of many materials in use or in „Hibernation" is larger than the total amount of substances in landfills or in emissions.

Since urban metabolism is characterised by large linear flows and increasing stocks, a shift in the strategy for environmental protection is necessary. The main focus in the future should be the analysis and control of the anthroposphere. In order to use materials efficiently and in an environmentally sound manner, the urban metabolism must be understood. MFA, comprising of the systematic analysis of substance flows and stocks, has proven to be an excellent means to facilitate this shift of focus from the environment to the anthroposphere. It enables decision makers to abate environmental impacts by the most efficient means along the pathway of materials from the sources to the sinks. The MAc TEmPo case studies also confirmed, that MFA is a useful tool for synthesis, too, e.g. to design future scenarios of goal oriented resource utilisation.

Case study results: Three types of MFA case studies were performed: The substance metabolism of cities was investigated; the flows and stocks of chlorine and chlorinated compounds in Western Europe was assessed; and scenarios for the management of mass goods such as water, biomass, and construction materials were studied in view of sustainable development. The main results of the case studies are summarised below. Further details can be found in the Annexes B1 to B4, or in the case study main reports.

Metal metabolism of cities: The main objective of the two case studies on Stockholm and Vienna was to examine the flows and stocks of selected materials (i.e. Al, C, Cd, Cr, Cu, Fe, Hg, N, Ni, Pb, and Zn) through the anthroposphere of these cities. The MFA studies from both cities allowed one to compare anthropogenic substance flows and stocks with geogenic flows and stocks. This served for early recognition of future environmental loadings and to set priorities/ define measures to protect the environment in urban areas. For the first time, metal inputs and stocks in a city (Stockholm) were analysed and modelled for a long period (95 years), an approach which required new assessment methods. The stocks were divided into sectors of use, degree of exposure to corrosion and in areas of responsibility for the goods. The study in Stockholm, which was performed in close co-operation with the Local Environmental Government and the Swedish Environmental Protection Agency, revealed high concentrations of cadmium, lead and mercury in sediments, soil and ground waters. The model used in Stockholm included responsibilities for the management of materials, and thus served to find actors and operators. It was also suited to include value analysis, which is important when evaluating the shift of a material from "In Use" to "Hibernation"".

The following conclusions were drawn: it is possible to determine the stock of goods and substances in urban centres even over long time periods. Concerning mass goods such as water, air and fuels, today’s cities are linear flow through reactors i.e. materials flow directly through the city and from a bulk material perspective recycling does not exist. There is an ever increasing stock of construction materials and consumer goods stored in cities. The accumulation of metals in cities is large, while the emissions so far are small in relation to the stock. Stock emissions are not well known. Thus, most environmental concern should be directed to manage the stock in order to minimise future impacts. Older domains of use often dominate the stock. Some of the goods, i.e. "dead electrical cables", are no longer in use and are forgotten "resources". The responsibility for managing these forgotten materials is unclear. MFA enables one to detect such hibernating materials. MFA can serve as a base for environmental indicators. Such indicators should be based on the anthroposphere (use of materials) rather than on the environment (concentrations in air, water and soil).

Chlorine compounds in the EU: The main objective of this study was to give an overview of the flows and stocks of chlorine and chlorinated compounds within the Western Europe. In particular, the project identified hazardous flows, described trends and explored various control measures. A number of flows, which were methodologically difficult to determine were studied in detail, such as emissions and wastes from stocks of PVC and CFCs, and emissions of chlorinated micropollutants.

The following results were obtained: There is a large stock of PVC in the anthroposphere. Hence, if the use of PVC is phased out within the next 10 years, PVC waste flows will still be generated over the next two centuries. This can be shown with simple models. From the study of world-wide CFC stocks, it can be concluded that there will be emissions of CFCs for the next 50 years from accumulated stocks, even if the use in developing countries would decrease just as fast as in the developed countries.

The study of chlorinated compounds in the Netherlands reveals, that there is an important gap in the current knowledge about emissions of chlorinated micropollutants. A number of ways to improve the understanding of these emissions have been identified. For example, a comprehensive monitoring program could be carried out to identify individual compounds in these emissions. This research could be coupled with research to determine the persistency and bioaccumulative potential and toxicity of these compounds. Alternatively one could bypass identification and focus more on the total emissions. In both the Dutch Chlorine Chain study and in the MAc TEmPo case study of flows of chlorinated compounds in Western Europe, it was found that MFA can be a powerful decision supporting tool: MFA can be an important aid to focus discussions and to help reduce uncertainties by providing structured data.

SYNOIKOS: This project is part of the large programme called SYNOIKOS investigating the restructuring of a region in the Swiss Lowlands in view of sustainable development. The main objective was to elaborate material management models for water, biomass and construction materials, and to develop long term scenarios with regard to concrete goals of regional development, such as " sustainability" and regional self-sufficiency. The results of SYNOIKOS have been implemented into regional policy through workshops with local leaders (political, economic, social). A new project titled: „Stadt der Wigger“ has begun leading into the development and management of regional action plans by regional enterprises (public and private).

The following conclusions from SYNOIKOS were drawn:

Water regime: In the Synoikos region, systems for water supply as well as waste water collection and treatment are highly developed. The region depends on ground water as a source of drinking water. The quality of this source is gradually decreasing mainly due to agricultural activities. An appropriate hydrological model for regional water management is still lacking. Such a model is indispensable to evaluate scenarios regarding the sustainable use of water resources. Nitrate concentrations in the groundwater are still increasing (very slowly). If no additional measures in agricultural practice are taken, then drinking water quality limits on a long-term scale could be exceeded. This regional metabolic process does not fulfil the criteria of sustainability.

Biomass: The case study focuses on wood and shows, that today, wood is not a scarce resource anymore in this region. Even at a high consumption rate of about 0.5 t/c.y, the degree of self sufficiency in the study region amounts to 85 %. Scenarios were developed to get a better understanding of the future role of wood as a renewable resource. The project revealed, that regional forestry should be directed towards the production of timber rather than paper. Sustainable forestry practice alone is insufficient to attain sustainable regional management of wood. In addition, production, processing, consumption, and disposal of wood have to be well balanced.

Construction materials: Flows and stocks of construction materials and construction wastes were analysed, and the effects of control measures on material and energy flows were investigated by modelling three scenarios. It was found, that for sustainable management of residential buildings, the key factor is the energy demand for the building's operation, and not the amount or kind of construction materials used. Thus, energy policy concepts focusing on sustainable development must also take into account the long-term goals of settlement policy. As the existing stock of residential buildings determines the energy demand of the system, its future development depends upon the change in the settlement area. A significant reduction of energy consumption can only be reached, if the stock of residential buildings stops growing and the existing buildings are raised to the highest available standard of energy conservation.

IV Scientific Interest and Novelty

The MAc TEmPo project indicated clearly the need to shift the focus in environmental protection research from the analysis of the environment to the understanding and control of the anthroposphere. It is suggested that a new research agenda be established in order to further the discipline of the "metabolism of the anthroposphere". This agenda must include several disciplines from natural sciences to engineering to social sciences. The ultimate goal of this agenda is to supply the necessary tools to design future anthropogenic systems in view of long-term environmental protection and resource conservation.

The MAc TEmPo group has demonstrated, that MFA is a well developed and readily available, rigid method for the analysis of metabolic processes of regions. It can be used to simplify the complex system "regional metabolism" so that the important flows and stocks of materials become clear. It is an indispensable tool to assess the flows and stocks of materials in the anthroposphere. Together with mathematical modelling, MFA serves as a strong base for the management of resources and the environment. The case studies have shown comprehensibly, that MFA scenario modelling can yield new solutions with regard to the sustainable management of resources.

The methodology of MFA has been further developed and clarified. Terms such as goods, processes, materials and substances, have been discussed, and new terms such as Hibernation and Hinterland have been introduced. It is up to the applied community now to use and eventually further develop the present set of terms and definitions. With respect to modelling, four partners have elaborated their own products, which they present now intend to market. The ultimate goal of a dynamic model for the anthropogenic metabolism will be further pursued.

Innovative work within the MAc TEmPo project comprises also the historic and systematic treatment of the accumulation of materials in urban systems ("stock problem"), and the link of several disciplines (MFA, regional planning, statistics and economics) in order to design future resource management scenarios.

The propose research agenda involves:

- collecting more data, comparing the material flows and stocks of cities and their Hinterlands in several European regions.
- creating a data base system which allows data collection and treatment in a systematic “cradle to grave” manner.
- developing a methodology for evaluating **stocks** in terms of environmental loadings and future resources.
- developing design tools for urban metabolism which are capable of incorporating MFA methodology data and results.
- creating new computer based models to treat the dynamic case of material management systems.
- constantly evaluating the use of MFA in the political decision making process

V Policy Relevance

The first experience with MFA in Europe dates back to the beginning of the 1980´s. The early projects focused mainly on methodological development. Case studies well suited for evaluating the use of MFA as a tool for policy decisions are still rare. In addition, as stated before, the MAc TEmPo project included only one policy science expert. Hence, the following findings are to be regarded as first assessments. They are based on the experience of the case studies, and have been collected by a questionnaire elaborated within the framework of this project. In general, the case studies showed that MFA is a useful tool for policy decisions regarding the management of resources.

MFA is well suited to visualise the complex regional metabolism. It is based on the principle of the conservation of mass (input equals output), and thus is easily understood by decision makers (“what goes in must come out”). It is a highly transparent tool, and provides a good basis for comparing a set of scenarios. MFA systematises and integrates information coming from different disciplines. If all assumptions about system boundaries and the selection of processes and goods are known and documented, an MFA research permits an objective discussion of environmental and resource policy measures.

Arguments from different stakeholders in the political debate can be formulated and tested against the information provided by MFA. The common language of MFA allows one to systematise and integrate information from different disciplines. Thus, MFA improves the ability of the actors to define a common platform with regard to the current situation, and to participate in the development of future scenarios by visualising the consequences of certain measures at an early stage. Hence, “operators” and their clients should use both this new and efficient tool together to find a common platform and to reach effective decisions. “Operators” could include decision makers on all levels, such as entrepreneurs, city officials, Ministries of the Environment etc.

The formation of stocks and subsequent material flows from stocks can, on the one hand, reduce the effects of source (consumption) related policy measures. Thus, policy decisions regulating environmental protection must always be based on a complete set of data, including all major flows and stocks. MFA can provide such a complete set of information. On the other hand, knowledge about the formation of stocks allows one to design new resource utilisation strategies such as an “urban mining” strategy. Anthropogenic materials built into the city may become the main source of raw materials. If resource conservation policies are directed towards the new goal of urban mining, new tools are necessary, e.g. in the field of information (material databases) and technology (design for urban mining).

Often, public awareness for an environmental problem is a vital promoter for the MFA approach. In many cases, MFA provides the basic information needed to solve a specific problem. Up to now, only in a few cases has public interest arisen by an MFA research, e.g. CFC stocks in construction materials or diffusive emissions from metal stocks in cities. One reason for this shortcoming might be that MFA is still primarily used and discussed among scientists and experts. Another drawback of MFA is, that the results sometimes cannot be immediately translated into action, because the system in question cannot be directly influenced by the particular decision maker.

MFA is useful to forecast the effects of social and economic developments on materials management systems. This forecast must be based on data on the current material stocks, on an analysis of the materials management system, and on assumptions about the developments of technology, economy and human behaviour. In a decision making process MFA provides information about possible future “problem shifts” and thus serves as a base for long term planning. If MFA is applied repeatedly to the same system (“materials accounting”), it can be used to evaluate the success of policy measures, and to create and enhance awareness of future problems.

As stated in the Results - Materials accounting Case Studies (III.2), a major conclusion of MAc TEmPo is to shift the focus from the environment to the anthroposphere. In order to start this change, decision makers must become familiar with the idea of urban metabolism and the accompanying tool MFA. This implies continuous efforts to build new capacities in the MFA field and to widely disperse the results. In the first place, these new tools must be provided and integrated into the fields of planning and development. Producers of investment goods (e.g. infrastructure) and mass products (e.g. consumer goods) with long residence times should also be addressed. Continuous education curriculum in the field of sustainable development must include the methodology of MFA on all levels.

Another important shift revealed by the results of MAc TEmPo is the need to design certain measures for environmental protection and resources conservation on a regional level, too. The geogenic as well as the anthropogenic conditions (e.g. dilution potential in water and air, population density) can vary from region to region, thus posing different problems and solutions for individual regions. In the future, it is important to find an appropriate mix of regional, national and global measures for resources protection based on MFA.

The shift of emphasis from the environment to the anthroposphere mentioned above requires new instruments on the administrative and policy level. Traditional administrative bodies are directed towards environmental protection, focusing on administering the flows of emissions and wastes on the one hand and the materials supply on the other hand. Today, there are a few administrative bodies which concentrate primarily on materials management in view of sustainable development. Thus, it is important to establish offices for materials management on regional, national and European levels, which eventually may replace current environmental protection positions. Such a change seems possible only if new policy strategies are established which focus more on efficient and total resource management rather than on singular *ad hoc* forms of environmental protection.

Today, a general data base for MFA does not yet exist. Future collection of statistical data should also be directed towards MFA. This means, that not only information about goods should be compiled, but also about substances contained in these goods. In the first place, a data base system should be developed in order to systematise the collection and treatment of data on all levels. Case study examples could highlight for decision makers how MFA can be used and how corresponding databases permit efficient materials management. Ultimately, a system for materials accounting could be established similar to financial accounting systems. In view of the MAc TEmPo team, the information developed within this project is not sufficient yet to prescribe a procedure for data collection to be followed by statistical offices. The question of how national and European statistical offices should collect and treat goal oriented data for MFA purposes requires further consideration.

VI Collaboration

VI.1 Collaboration with other EU research projects

- “Economic Assessment of Priorities for a European Environmental Policy Plan” is a study financed by DG XI in the framework in the 6th Environmental Action Program, co-ordinated by the RIVM together with the University of Athens, CSERGE and the RUL.CML. The main object in the project is to integrate these three groups into one framework of “integrated environmental assessment”, in order to provide opportunities for the EC to compare different options for the abatement of environmental problems with regard to their cost-effectiveness.
- RUL.CML has been co-ordinating the LCANET, a concerted action financed by the Environment and Climate Program. The main goal of the project is to exchange information and to define the future research agenda of on another policy supporting analytical tool: LCA.
- RUL.CML is co-ordinating CHAINET, a concerted action financed by the Environment and Climate Program. The main goal of the concerted action is to link supply and demand of information and to create a toolbox with different environmental tools.
- TUW.IWAG has formed a consortium, financed by the PHARE Program of the European Community, to apply materials accounting methods to analyse and solve nutrient related water quality problems in the river Danube basin (Danube Applied Research Program: Nutrient Balances for Danube Countries; EU/AR/102A/91).

- ConAccount is a concerted action financed by the Environment and Climate Program. It is co-ordinated by the Wuppertal Institute together with the Institute for Interdisciplinary Research and Continuing Education Vienna, Statistics Sweden and RUL.CML. In January 1997 the first ConAccount workshop was organised by RUL.CML. The co-ordinator of MAc TEmPo is a member of the Advisory Board of ConAccount. Most of the MAc TEmPo teams presented their work at this meeting.

VI.2 Complementary with other research in the field

- The case study SYNOIKOS of the EAWAG.RWM group is also part of the Alliance for Global Sustainability - a collaboration of the Massachusetts Institute of Technology, the University of Tokyo and the Swiss Federal Institute of Technology Zurich.
- The Dutch Foundation for Scientific Research (NWO) financed a study performed by four Dutch Universities and co-ordinated by RUL.CML on the flows of heavy metals through the anthroposphere and the environment in the Netherlands with case studies for building sector and the agricultural sector. The MAc TEmPo project brought together the groups working on metals in the MAc TEmPo project and the Dutch Universities working in the NWO project in contact with each other.
- In order to complete their case study, the Dutch group RUL.CML has several collaborations with partners and projects outside of the MAc TEmPo group: For Norsk Hydro, TNO and CML performed an MFA for PVC and its additives in Sweden as an input for the Swedish PVC debate. The insight in PVC flows and stock formation in an EC-member state has been used, together with information on flows and stocks in other member states, in the chlorine case study in the MAc TEmPo project.
- RUL.CML was commissioned by the RIVM to generate ideas about how the results of MFA can be translated into indicators which can be used in environmental policy plans and progress reports.
- The results of the case study of the ULIN.TEMA.WE team will also be incorporated into the Swedish Environmental Protection Agency research programme ”Metals in the Urban and Forest Environment - Ecocycles and Critical Load, 1994/95 - 1998/99”. Bo Bergbäck is co-ordinator for the urban portion of this project.
- TUW.IWAG conducted a comparison between the results of the anthropogenic metabolism of the city of Vienna with the natural metabolism of the regional biosphere. The study was financed by the City of Vienna (Paumann R. et al. Wechselwirkungen zwischen anthropogenem und natürlichem Stoffhaushalt der Stadt Wien; Vienna, 1997). This project allows to evaluate the implications of the anthropogenic flows and stocks and to draw conclusions regarding the future management of selected materials in Vienna.
- A research project of TUW.IWAG together with the Chair of Political Science of the Salzburg University, Austria has been awarded funding from the Austrian Science Research Foundation. This project aims to investigate the use of MFA in the political decision making process using case studies from a political science point of view.

VII List of Publications

VII.1 In preparation

Bergbäck, B., Brunner, P.H., Lohm, U. & Obernosterer, R. "Urban Metabolism - Growing stocks and unknown emissions", *Water, Soil and Air Pollution,* to be published in 1999.

Brolin, P.; Lindström, M.; Håkansson, L.; Jonsson, A. Modelling the dispersion of heavy metals from Stockholm. *Water, Soil and Air Pollution,* to be published in 1999.

Hedbrant, J. Modelling of metal metabolism in Stockholm. *Water, Soil and Air Pollution,* to be published 1999.

Hendriks,C., Müller, D., Obernosterer, R. & Brunner, P.H. "Material Flow Analysis (MFA) - a tool for regional environmental and resource management", *Local Environment*, To be published June 1999.

Jonsson, A.; Svidén, J. The use of mercury in Stockholm during the 20th century. *Water, Soil and Air Pollution,* to be published 1999.

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Müller D. (1998). *Stoffhaushaltsmodell zur regionalen Bewirtschaftung von Holz*. Dissertation, PhD-thesis, to be published in 1998. (ETH Zürich)

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VII.2 In press

Bergbäck B & Jonsson A. (YEAR) "Cadmium in goods - contribution to environmental exposure". *The Swedish National Chemicals Inspectorate*.

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VII.3 Published

Bauer, G., Deistler M., Gleiß A., Glenck, E., Matyus T., (1997) "Identification of Material Flow Systems", Environ. Sci. & Pollut. Res. 4 (2) 105 - 112

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VIII Other Information Activities

The results of this project will be disseminated by:

- publications in scientific and applied journals and books (e.g. the Eurpoean Envirionment Agency's (EAA) State of the Environment Report),
- presentations in workshops, seminars and conferences, particularly addressing the cities, regions and authorities which were involved in the case studies (cities of Stockholm and Vienna, Synoikos region, Sweden, EC)
- incorporation into the regular curriculum of academic graduate, post graduate and continuing education in the fields of civil engineering, environmental engineering, regional planning, urbanism,
- developing homepages on the world wide web, and by future applied research projects collaborating with "operators" which will eventually become promoters of the MFA concept.
- a popular edition of the report aimed at a policy audience

The methodology and results of MAc TEmPo have already been incorporated in the regular curriculum of civil engineering education at ETH Zürich, Tema Linköping and TU Vienna, helping the future engineer to master MFA and to understand the basis of urban material management. In addition, courses on the use of MFA for environmental management and auditing have been organised by individual MAc TEmPo teams.

The visualisation of anthropogenic metabolism by MFA increases the awareness for possible environmental impacts and/or resource potentials from anthropogenic urban flows and stocks. Thus, means for presentation such as an internet interface will be developed for various levels, from school to continuing education. As an example, the Stockholm Environmental Government is most concerned to have an interactive link with the „Stockhome" model and other data bases within the framework of the Local Agenda 21 programme. The same applies to the city of Vienna, which intends to use MFA tools in the implementation of Local Agenda 21, too. This work will be intensified during 1998.

MAc TEmPo results are, in part already and will be more, linked to data bases like Con-Account/Wuppertal or the Substance Flow Database in development by the Social Ecology Department at the Institute for Interdisciplinary Research and Continuing Research, University of Vienna .

The "know-how" transfer from the scientific community to the applied engineer in the field is of high priority in order to establish a critical mass of practitioners using MFA and acting as disseminators of the methodology. This process has already begun in connection with national professional associations in Switzerland and Austria, and it will be continued in the future.

On the European Union level, the results of MAc TEmPo will be submitted for publication in the next edition of the EEA'S the "State of the Environment in Europe", and they will be presented to and discussed with the DG XVI responsible for urban development.

IX Other Observations

A significant outcome of the MAc TEmPo project has been capacity building. In the course of the study and because of the financial support of the EC, the materials accounting community has grown in size, strength and co-operation. In general, the concept of "urban metabolism" has been spread by this project. In addition, MAc TEmPo enabled the participating teams and other groups to initiate further research projects in this field.

During this study, it became clear that the social science side of assessing MFA policy implications is important, and that this issue should be tackled by experts from the field of social sciences. Hence, the teams recognised the need for future collaboration with partners from these disciplines. Recently, members of MAc TEmPo have successfully submitted a combined social science and MFA proposal for funding by the Austrian Science Foundation.

In the MAc TEmPo project, the experience with advisory boards was a productive way of extracting political input. However, the process could have been improved by:

- maintaining closer co-operation with stakeholders through more intensive and regular workshops
- addressing future decision makers - not only those from the political arena but also representative other sectors e.g. from economic, mineral and education sectors
- involving stakeholders with a critical attitude towards MFA
- maintaining interest in MFA discussions by providing the opportunity for both technical and political input. A balance must be found where both the technical and political audience remains involved.

PART B: ANNEXES

1 - 5

Case Study Reports of the Contractors

ANNEX 1 to SUMMARY REPORT
Report of the contractor TUW.IWAG

URBAN METABOLISM
The City of Vienna

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1 Objectives

1.1 Introduction

Since the 1992 UN Conference in Rio de Janeiro, considerable discussion and research regarding environmental concerns has revolved around sustainable development. Currently, the emphasis is on how to translate this concept into the policy making process on all levels. The tool Material Flow Analysis (MFA), which is introduced in this study can be implemented on administrative and private policy levels to support the decision making process as we move towards sustainability. MFA has a high potential to be implemented as a guiding tool on the regional level. For example, as part of a Regional Environmental Management and Audit System (regional-EMAS) or as a part of the Local Agenda 21 Process.

Material Flow Analysis (MFA) is a complementary tool to traditional environmental and resource management approaches. It provides the necessary links between anthropogenic activities and their impacts on the environment. In a policy sense, MFA has been used for early recognition, to set priorities, to analyse and improve the effectiveness of measures and to design efficient material management strategies in view of sustainability.

This project, which was financed within the 4th European Commission Programme for Environment and Climate, involves five partners from The Netherlands, Sweden, Switzerland and two groups from Austria. This particular section of the project focuses on the metabolism of an urban area, the City of Vienna.

Urban regions typically induce high energy and material flows, due to high population densities and their huge and relatively dense material stocks. Knowledge about the metabolism of cities should be of great interest to decision makers since this information allows them to react to and prepare for present and future issues regarding materials flows and stocks of a city.

1.2 Goal of the Study

> The main objective of this study was to examine the metabolism of the City of Vienna by means of **Material Flow Analysis** (MFA) and to explore the use of MFA in the decision making process in view of environmental protection and resource conservation.

Three different interconnected investigations were carried out to gain a holistic understanding of the urban metabolism:

I. Anthropogenic Metabolism

Objective: To identify the key anthropogenic material flows and stocks within the City of Vienna. The results of this investigation are essential for the design of efficient material management strategies within the anthroposphere.

II. Linking the Anthropogenic and Natural Metabolism

Objective: To understand the interaction between the anthroposphere and the environment. In particular, to assess the current anthropogenic material flows into the environment and to investigate the effect on the environment due to decisions made within the anthroposphere.

III. Linking the Metabolism of the City with the „Hinterland“

Objective: To assess the dependence of the City of Vienna on its „Hinterland“ for supply and disposal of materials.

2 Methodology

The approach Material Flow Analysis (MFA) was used to describe the metabolism of the City of Vienna. The methodological steps were similar to those used in existing studies, such as Baccini & Brunner (1991), Brunner et al. (1990) and Baccini & Bader (1996). The new challenge in this project was to apply the MFA approach to a large urban region and to investigate „Hinterland“ relationships. During the course of the project, the importance of highlighting stocks became apparent. The term „Material Flow and Stock Analysis“ (MFSA) was therefore created which replaces the term MFA in this report from hereon.

MFSA is based on a holistic approach which examines the materials flowing into a given system (private household, company, region, city etc), the stocks and flows within this system, and the resulting outputs from this system to other systems. Furthermore, MFSA focuses on loadings rather than concentrations. MFSA can be used quantitatively by looking at „goods“ (concrete, biomass, cars etc.). MFSA can also be used on a qualitative level to examine the potential environmental harm or resource potential of the flows and stocks of substances.

In previous MFSA studies, geogenic references have been used as a reference point for sustainability. This approach was also used by the Vienna team to indicate the „gap“ between the current urban metabolism conditions of Vienna and geogenic conditions (prior to settlement).

System Definition

In this project, the City of Vienna was subdivided into a number of key processes. The flows and stocks of goods within the system were initially investigated in order to identify the most important substance carriers. In order to understand the system on a substance level, six indicator substances were selected for investigation: Carbon and Nitrogen (essential nutrients for the biosphere), and Aluminium, Iron, Zinc and Lead (some of the most important metals in the anthroposphere). Three different interconnected investigations were carried out (as mentioned above in Section 1.2.).

The temporal system boundary for all three investigations was a period of one year and the selected year was 1991. This time frame was primarily selected due to data availability, practicability and compatibility. The spatial system boundary for investigation I (Anthropogenic Metabolism) and II (Linking the Anthropogenic and Natural Metabolism) was the administrative boundary of the City of Vienna. This boundary was selected for two reasons. Firstly, this system is compatible with the policy decision making framework of the City of Vienna. Secondly, the availability of data within this selected boundary is relatively good. The spatial boundary in investigation III (Linking the City with the „Hinterland“) does not follow a common geographical boundary. Instead it was defined by incorporating those key-processes and materials into the system which represent the issue under investigation. Within all three systems, the material flows between the key processes were investigated. The methodological steps involved in each system were identical.

Data

To date, no operational data base for MFSA exists. There is far more data available on the level of goods than there is on the level of substances. Information (data bases) necessary for MFSA on the waste and waste water management sectors and on private households is more abundant then information from industry, trade and service sectors.

For this project no specific measurements were carried out. Existing data from many varied sources were used to create the MAcTEmPo case study of Vienna. Three previous investigations on the metabolism of Carbon, Nitrogen and Lead within Vienna provided a base for the MAcTEmPo Vienna Case Study (the anthropogenic metabolism [Daxbeck et al. 1996], the natural metabolism [Maier et al. 1996] and the connection between the anthropogenic and natural metabolism [Paumann et al. 1997]). Further data bases are provided in the case study report (see reference list in Obernosterer et al. 1998a).

3 Main Results obtained

3.1 Results of the Metabolism of the City of Vienna

3.1.1 Anthropogenic Metabolism

Flows and stocks of goods within the City of Vienna:

- The flow of goods through Vienna amounts to 200 t/c.y (tons per capita and year). Approximately 90 % of this amount consists of the „goods“ water and air which are used within the anthroposphere. At present, Vienna is essentially a “flow through” reactor for the most of important mass goods (water, air, and energy sources). The city is therefore, highly dependent on its „Hinterland“ for supply, as well as for disposal of its residuals.
- The import of solid goods into the city exceeds the exports, and hence there is a stock build up of 350 t/c. If the input and the output of the stock remains constant then it is expected that the stock will double in the next 30 to 100 years.

- The flow through of goods through the private households is in the same order of magnitude as the flow of goods through the industrial and trade sector. This indicates that Vienna is not only a service region, but also has a significant production sector.

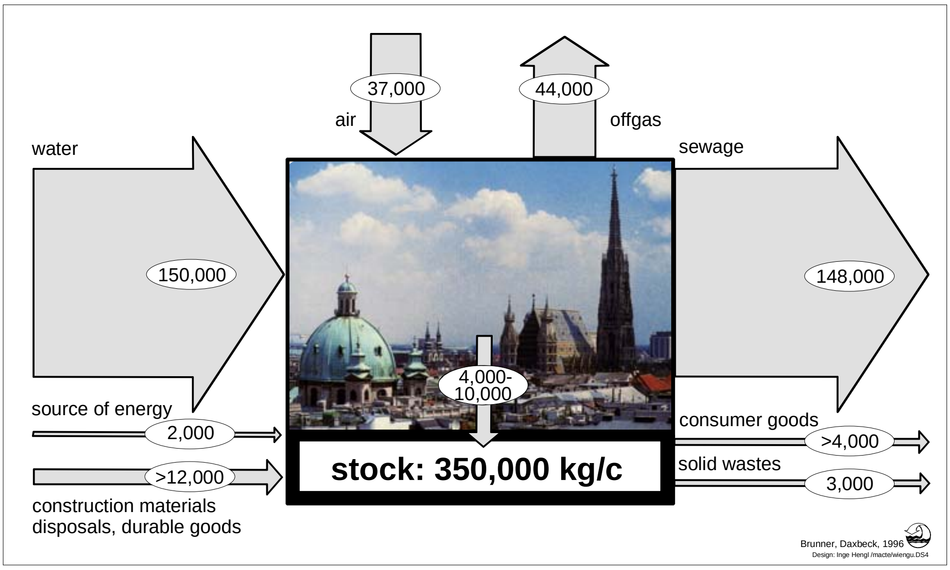


Figure 3-1: Flows and stocks of goods in the anthroposphere of Vienna in 1991 [flows in kg/c.y; stock in kg/c]; population of Vienna - approx. 1.5 million

Flows and stocks of substances within the City of Vienna:

- The Carbon flows within Vienna (3 t/c.y) are primarily related to the consumption of fossil fuels. Thus, the key activities to control the Carbon flows within the City are „to reside“ and „to transport“. Nitrogen flows (30 - 40 kg/c.y) are due to the activities „to nourish“ and again „to transport“ and „to reside“.
- Today, the important stocks within the City of Vienna are the building and infrastructure stocks and not the landfills. These urban stocks are steadily increasing by 1 - 3 % per year. In general, between 70 and 90 % of the stocks investigated are found within the city's buildings and infrastructure. The Carbon stock in Vienna's buildings and infrastructure (33 t/c) increases by 1 - 2 % per year and for Nitrogen stock it increases by 1.5 - 3 % per year. For the investigated metals, Lead, Iron, Aluminium and Zinc, the flows into the stocks are larger than the output flows. In the future, these stocks will be potential resources and/or pollutants and will need to be recycled or disposed of in some way.

3.1.2 Linking Anthropogenic and Natural Metabolism

Results of flows and stocks of substances within the City of Vienna (anthroposphere and connection with the environment):

- Viennese conveyor belts (river Danube and air throughput) have a high dilution potential and therefore established „concentrations limits“ are generally met. However, the link between the anthroposphere and the environment shows that the anthropogenic activities are altering environmental conditions. For example,

⇒ the link to geogenic conditions (past environmental conditions prior to human settlement) shows that today's anthropogenic loadings into the air and water for the substances Carbon (CO_2, DOC), Nitrogen (NO_x, N_2O, total N) and Lead (Pb) are 25 - 800 times higher than comparable past loadings from a „geogenic“ Vienna.

⇒ the link with the current environmental conditions shows, that there is an increase of substance concentration in environmental media, e.g. the concentration of Pb and N in environmental media increases by approximately 0.1 and 0.3 % per year respectively.

⇒ the current concentration of Nitrogen in the river Danube in Vienna does not indicate the increase of Nitrogen in the Danube Delta and in the Black Sea. The increases however, can be highlighted, by following substance loadings to their final sinks.

- The above examples indicate that environmental assessment should consider not only concentration limits but total loadings and final sinks, especially in relation to long-term environmental effects.

3.1.3 Linking the City with the „Hinterland“

„Hinterland“ investigations in relation to the City of Vienna:

- It is possible to examine the relationship between an urban region and its „Hinterland“ using MFSA.
- In some cases, the induced flows in the „Hinterland“ are more significant than those in the city system itself. The first investigations into the relationship between a city and it's „Hinterland“ using MFSA (relaying on many assumptions) reveals that:

⇒ the Nitrogen flows into the river Danube, induced in the „Hinterland“ are 2 times larger than those flows directly coming from the city itself (primarily due to the activity „to nourish“).

⇒ about 60 % of the Carbon flows related to transport fuels are emitted by the Viennese as „shadow emissions“ through transport and leisure activities outside the city.

⇒ significant Lead emissions are released in the „Hinterland“ due to the processing and recycling of car batteries demanded by the Viennese.

3.1.4 Comparing Viennese Results with other MAcTEmPo Teams

A comparison between the Viennese Results and the results from the other MAcTEmPo project teams is useful both from a methodological and „results“ point of view. By comparing the different case studies some results can be confirmed, and any shortcomings or failures can be detected. Some key comparisons include:

- The Carbon input from energy sources in the Swiss Lowlands is approximately 2.0 t/c.y and in Vienna approximately 1.7 t/c.y. In the Swiss Lowlands, Carbon is released within the system, whilst for Vienna approximately 0.4 t/c.y are released in the „Hinterland“.
- The flows and stocks of gravel and sand consumption in Vienna and in Swiss Lowland are remarkably similar (see Table 3-1).

Table 3-1: Comparison of flows and stocks of gravel and sand of Vienna with Swiss Lowland

Flows and Stocks	Vienna	Swiss Lowlands
construction material input (t/c.y)	5-10	8
construction material stock (t/c)	350	340
demolition waste (t/c.y)	1.6	3

- The flow of surface water through the KSM-system (region in the Swiss Lowlands) is approximately 100,000 t/c.y, mainly due to the River Aare; whilst in Vienna it is approximately 33,000 t/c.y mainly due to the river Danube. This highlights the different dilution potential of the two regions per capita.
- The Stock of Zinc in Stockholm was calculated to be 40 kg/c whilst in Vienna the Zinc stocks are up to 100 kg/c. However, other MFSA Zinc studies [Daxbeck et al. 1997; Baccini & Bader 1996] indicate that Zinc stocks are in the order of 300 kg/c. At this point in time it is unclear if the differences are related to methodological issues or if there are indeed large differences in Zinc stocks between different regions.
- A comparison between Vienna and Stockholm reveals that the Lead stocks in both cities are quite similar (65 kg/c in Stockholm, 100 - 200 kg /c in Vienna). There are however, some differences in the amount of Lead cable stocks which could be related to different settlement densities [see Möslinger 1998]. These differences could also be attributed to the fact that in Stockholm there has been no input of Lead cables since 1970.

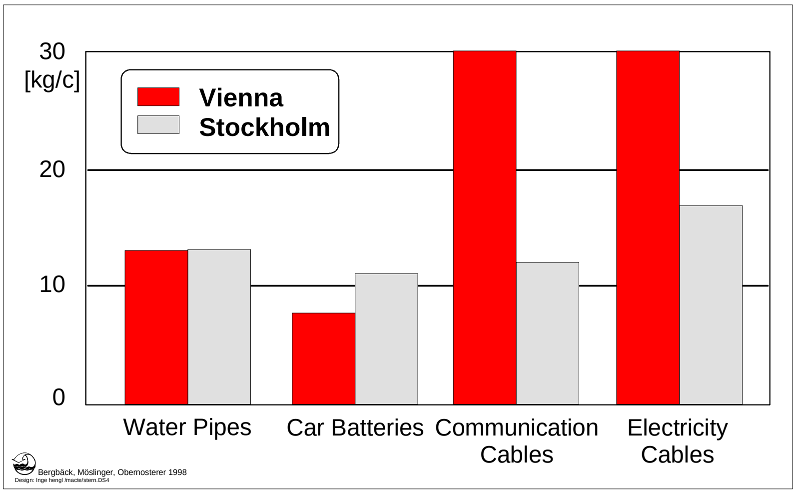


Figure 3-2: Comparison of Lead stocks in Vienna and Stockholm for four different applications (kg Lead / c).

3.2 Using MFSA for Environmental and Resource Policy Making

Studies on Material Flow and Stock Analysis (MFSA) have generally focused on the methodological and data issues of understanding material flows and stocks within a region or within other boundaries. Some steps have been made to introduce MFSA into the policy world by highlighting gaps or failures in existing policies. MFSA has also been used to make recommendations for future policy directions. Further steps now must be taken to bring together the science of MFSA with the economical and political spheres in order to determine the most efficient materials management scenarios. The MAcTEmPo project is one such bridging step, identifying the possible links between the technical MFSA world and its implementation into the policy world.

What follows is a description of the key policy uses of MFSA. Several examples are used to highlight the applicability of MFSA in the policy world. The examples do not necessarily represent recommendations in themselves.

3.2.1 Early Recognition - from reaction to precaution

MFSA allows for a precautionary approach since it can anticipate future environmental problems and does not rely on signals of „environmental“ stress. MFSA focuses on forecasting material flows and stocks and can be used to detect whether stocks are increasing or decreasing. MFSA, therefore, provides a strong basis for early recognition since it can identify future environmental problems or resource potentials. The following examples highlight how MFSA results can be used for early recognition purposes. The first example shows how MFSA can be used to forecast the increase of substances in environmental stocks. The second example discusses the importance of managing buildings and infrastructure stocks for future generations.

Early recognition of environmental problems

MFSA can identify future environmental problems by highlighting changes in the stock of substances in different environmental mediums. For example:

- Today the average Lead content in Vienna’s top soil is approximately 60 ppm (measurements between 20 to 700 ppm). If the current Lead inputs remain constant, then the recommended allowable average level of 100 ppm Pb [Eikmann & Kloke 1993] in the topsoil (10cm) will be exceeded in the next 250 years.
- Currently, the average Nitrogen (NO_3) content in Vienna’s upper groundwater layer is approximately 54 mg NO_3/l which exceeds the Austrian standard of 50 mg NO_3/l. If the current Nitrogen input into the groundwater remains constant, then the NO_3 concentration in 10 years will be approximately 70 mg NO_3/l and in 100 years 220 mg NO_3/l.

Early recognition of stocks

About 90 % of city’s metal stock is located in Vienna’s buildings and infrastructure, whilst only 10 % is in the landfills. Current environmental policy controls, however concentrate heavily on landfill stock emissions.

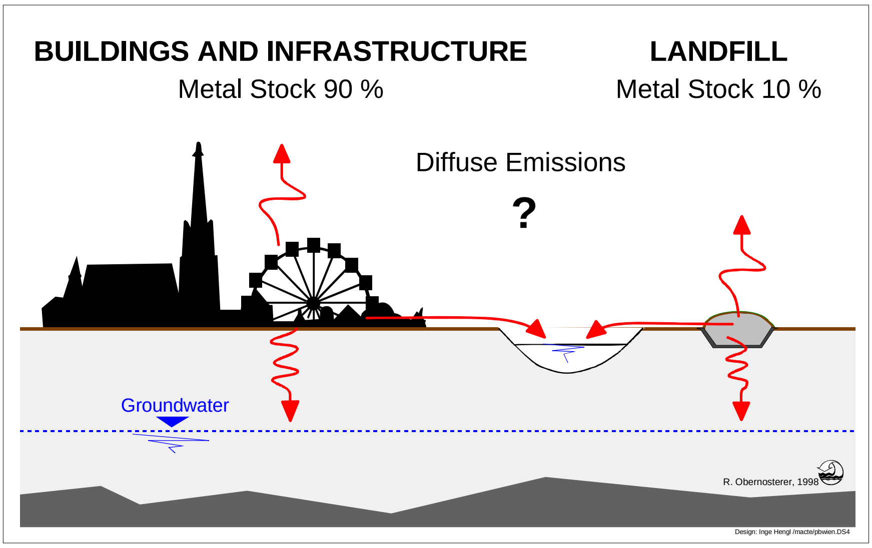


Figure 3-3: Metal stocks and their potential diffuse emission pathways in Vienna.

Further studies are required to identify which specific stocks contribute to environmental problems and/or those which represent potential resources. Some examples of evaluating stocks includes:

- the anthropogenic organic Carbon stock represents a potential environmental problem when disposed of in a landfill (where biochemical reactions release greenhouse gases such as CH_4 and CO_2) or a potential future energy source when incinerated before landfilling.
- the metal stock within the city represents a potential source of diffuse emissions. On the other hand these stocks represents a potential future resource, as discussed in the next section. The sources of diffuse emissions within urban regions are explored in greater detail in the Swedish (ULIN.TEMA.WE) MAcTEmPo Case Study.

MFSA can be used for early recognition since it can identify stocks and their changes in both the anthroposphere and in the environment. This information can be used to discuss the potential of a stock as a future environmental risk or as resource.

3.2.2 Efficient Resource Management - from mining nature to mining cities

The identification of key flows and stocks using MFSA can serve as a base for efficient resource management strategies. Two examples are presented: the first presents the idea of stock-management strategies, and the second example discusses the efficient use of materials for urban expansion.

Possible management strategies for Lead stocks

The buildings and infrastructure stock of materials will require management in the future. Consider the possible resource management strategies of the stock of Lead water pipes in Vienna's buildings (amounting to a total of approximately 20,000 tons):

- *Re-use of stock*: City Mining of this Lead stock could provide enough Lead coated telecommunication cables for Vienna for approximately 30 years (assuming the demand for Lead cables remains constant) or enough Lead to produce approximately 1,600,000 traditional car batteries.
- *Disposal of stock:* For non-reusable materials, possibilities to achieve final storage quality must be found. If a Lead stock has a re-use potential, but no market for recycling today, a controlled disposal strategy in view of future use should be adopted.

Urban planing and resource management

Urban planing can have a significant impact on resource management particularly in controlling input flows. Planing high density regions will lead to a significantly lower per capita good and substance input than planing less densely populated regions (see also Obernosterer et al. 1998b and Möslinger 1998).

MFSA can be used for planing efficient material management strategies. It provides a basis for designing and optimising material flows and stocks. Furthermore, the resource potential of the current buildings and infrastructure stock for future use can be detected.

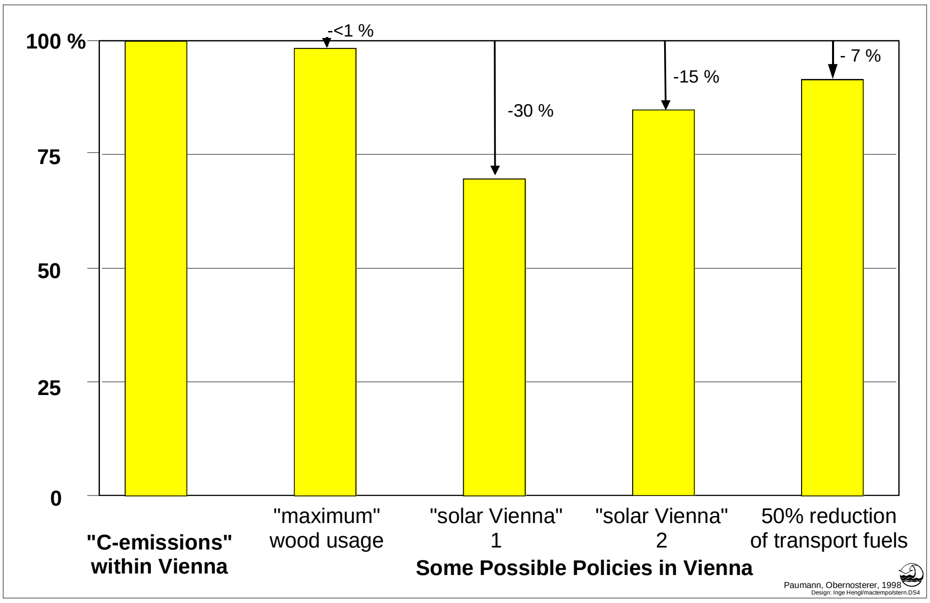
3.2.3 Priority Setting - from ad-hoc measures to efficient policy

MFSA is a useful tool for priority setting since it allows management strategies to concentrate on key issues and examine the effects of various material management strategies on the entire system. In the following two examples, the use of MFSA for priority setting is discussed in relation to examining ways to reduce Carbon emissions and to manage Nitrogen flows.

Carbon Metabolism - running scenarios of various management strategies in order to set priorities

In view of the „greenhouse effect“ a key question is, how can the Carbon flows into the atmosphere be reduced? There are a number of possible management strategies available to address this issue. MFSA provides a base to identify the potential success of each strategy in relation to substance reduction in the entire system.

Within the four different management scenarios presented in Figure 3-4, it is obvious that in view of reducing greenhouse gases, greater priority should be given to encouraging solar energy strategies than to maximising the use of Vienna's wood resources. This example is used to highlight the potential of MFSA as a tool for identifying priorities and does not present all the possible management strategies for reducing Carbon flows in Vienna (such as the possibility of mixing various strategies).



Current situation (1991): Carbon emissions from activities within Vienna's administrative boundary into the atmosphere = 100%.
Maximum Wood usage: optimisation of the use of available wood resources within Vienna's administrative boundary.
Solar Vienna 1: use of photo-voltaic cells (60-150 kWh/m2 /a) on an area equal to 100% of Vienna's roofs.
Solar Vienna 2: use of photo-voltaic cells on an area of 50% of Vienna's roofs.
50% reduction of transport fuels: ~halve the use of transport fuels within the city's administrative boundary.

Figure 3-4: The effect of some of the range of policy measures which could be taken to address Carbon emissions within Vienna

Nitrogen **metabolism**- *identifying key-flows to set priorities*

If the increasing eutrophication of the Danube Delta and the Black Sea is to be prevented, measures must be taken to reduce the Nitrogen loads. After examining all Nitrogen loadings into the river Danube (including those which are induced by Viennese activities in the „Hinterland") one can conclude that:

1. The city is not an independent system - the main Nitrogen key flows outside the city are important for the development of the city. The current input flow into the river Danube from the „Hinterland" is approximately 10 kg/c.y and from the city 5 kg/c.y.
2. In this case it is obvious that setting priorities to reduce Nitrogen flows must also take into consideration the „Hinterland". The most appropriate policy measures could be made within the city (e.g. influencing dietary habits - less meat products), outside the city (e.g. improved nutrient management) or a combination of both.

In order to set priorities for environmental policy, a thorough understanding of the anthroposphere (the key flows, processes, and stocks) and its links with the environment is essential. MFSA provides this holistic view of the system and therefore allows one to set priorities on the possible policy measures, ensuring efficient material management strategies. Furthermore, MFSA requires a link to economic tools in order for policy makers to set priorities in material management.

3.2.4 Effective Policy Measures - finding efficient strategies

Current environmental measures tend to focus on single issues with little consideration of the total system. In many cases this approach can be highly in-efficient since it may only be addressing a small portion of the total flows and stocks. The following two examples illustrate how MFSA can be used to evaluate the response of the total system (flows and stocks) in relation to various policy measures.

Effectiveness of existing CFC management policy

This CFC-example does not focus on just the City of Vienna but rather on the whole of Austria. Like many other industrialised countries, Austria regulates the use of chlorinated and fluorinated hydrocarbons in consumer products and in other goods in order to protect the stratospheric ozone layer. A MFSA on CFCs was conducted for Austria [Obernosterer & Brunner 1997] to evaluate the effectiveness of current reduction policies. The current front end regulations, which prevent the use of CFCs, have resulted in a decrease of CFC emissions in the short term. However, the medium to long term emissions from CFC stocks are not efficiently controlled since the current regulations on stocks concentrate on CFCs in refrigerators only. The MFSA results reveal that there is a significantly large stock of CFCs in construction materials. The future emissions from these stocks will be much more significant than from refrigerator stocks. MFSA indicates that to improve current CFC strategies, future management of CFCs must take into account all stocks, including their changes and emissions. The management of CFC is further discussed in the Dutch (RUL.CML) study and further exchange of ideas and data between TUW.IWAG and RUL.CML is planed following the MAcTEmPo project.

Assessment of the Austrian construction waste recycling legislation

According to the Austrian construction waste regulation, construction and demolition waste must be separated in view of re-use. The MFSA results for the City of Vienna provide a basis for discussion of the effect of a recycling policy on the current bulk flows in the construction sector. Using today's demolition techniques such a policy could, when fully implemented, reduce the amount of construction waste flows (not including excavated soil) going to landfill by 45 %[1]. The recycling potential of construction waste could only reduce the current use of virgin materials of gravel and sand by 7 %. Therefore a cyclic use versus a linear use of gravel and sand has a minor influence on gravel and sand resource depletion. In order to further reduce the use of virgin materials, alternative construction and planning approaches should be adopted such as focussing on higher density settlements. In comparison to Vienna, a project on the City of Zurich highlights that the recycling potential of construction waste could theoretically reduce the current use of virgin materials of gravel and sand use for buildings by 50 % (see EAWAG.RWM Case Study). Such a difference highlights the importance of developing regionally adapted policy strategies.

MFSA can provide a basis for assessing the impact of a particular policy on the total system. It can be used to assess the effectiveness of existing and future policy measures and as a basis for designing improvements.

[1] When excavated soil wastes are included into this calculation, the construction waste flows to landfill can be decreased by only 10%.

4 Conclusions and Recommendations

Material Flow and Stock Analysis should be implemented as a complementary tool to traditional environmental and resource management approaches. MFSA is a tool which provides a systematic understanding of the anthroposphere and it can provide an overview of the total system by linking the anthroposphere with the environment.

To date, studies on MFSA have primarily focused on the methodological description of material flows and stocks within a given boundary. The MAcTEmPo project has been a bridging step linking the „technical“ MFSA world with it's potential policy uses. Such uses include: early recognition; setting priorities; analysing/improving policy measures; and assisting efficient resource management. In this case study, the policy applicability of the MFSA was investigated in view of the metabolism of the City of Vienna.

The main conclusions and recommendations stemming from this study have been separated into urban metabolism, data requirements, capacity building and policy strategies.

Urban Metabolism

- The City of Vienna is essentially a "flow through" reactor for the most of important mass goods (water, air and energy sources). The city is therefore dependent on its „Hinterland“ for supply (e.g. fresh water and air), as well as for disposal of its residuals (water and air are the most important disposal conveyor belts for the City of Vienna).
- The material import into the city by far exceeds the export, thus the stock of the anthroposphere of the City of Vienna is growing. This stock of materials in Vienna is mainly in the buildings and in the infrastructure and not in the landfills. Currently, the composition of the stock within the city is similar to that in the landfills. In the future, this stock will be either a potential resource or pollutant which will need to be recycled or disposed of in some way. Comprehensive information and knowledge is needed on the type and composition of these stocks, the dynamics of their changes, and about how to control and manage them. Compared with the stock increase the "classically" discussed outputs such as waste waters or off-gases represent only minor substance flows.
- The link between the anthroposphere and the environment highlights that anthropogenic activities are significantly altering environmental conditions.
- The relationship between an urban region and its „Hinterland“ reveals that in some cases, the induced flows in the „Hinterland“ into the environment can be more significant than those in the city itself.
- Materials are defined as goods or substances. From a methodological point of view it is important to use these terms correctly. Furthermore, MFSA requires a focus on loadings and material stocks. In order to improve the comparability of current reports, the terms and the steps of MFSA should be standardised e.g. ISO. While such a standardisation for MFSA on a technical/methodological level is recommended, it is too early to develop MFSA material accounting, evaluation and also MFSA policy implementation standards.

Data Requirements

- It is evident that the results from material accounting studies are as good as the quality of the raw data. Basically, there is far more data available on the level of goods in Vienna than there is on the level of substances.
- To date, no operational data base for MFSA exists and therefore collecting data for MFSA studies is resource intensive. However, there are a number of different data sources which can be used to obtain the necessary information. The main data sources are statistical and technical reports as well as publications. In addition, interviews with specialists and skilled workers play an important role in extracting data for MFSA studies. It should be noted that there are a number of efforts to create MFSA data bases, particular on the level of goods.
- In order for MFSA to be broadly used in an efficient manner, a Material Accounting system (MAc) is required which involves periodically registering material data. Such an accounting system (MAc) could be operationalised by altering current data collection systems (eg. statistical departments, government agencies, enterprises etc.). In particular, data sets should include: information on both, goods and substances (input and output) and information where these materials are produced and used. Furthermore, these data sets should be collected in common units e.g. for the anthroposphere in mass flows per capita and per unit time (kg/c.y).

Capacity Building

- MFSA is a powerful education and communication tool. It can be used to visualise future environmental and resource management scenarios to decision makers and to the public.
- Several opportunities have been identified in order to disseminate the results of the MAcTEmPo Case Study Vienna. In particular, a presentation was given in conjunction with a member from the Swiss MAcTEmPo team (EAWAG.RWM) and also a representative from the City of Vienna at a seminar organised by the Internal Environmental Agency for Local Governments (ICLEI). It is planned to implement the results of this study into a possible Local Agenda 21 process for Vienna. In addition, it is anticipated that the results of this project will be published in relevant journals and used for education material in current and future curricula. In order to expand the number of MFSA experts, it is planned to establish a MFSA Focal Centre in Austria which will run a number of MFSA education and training programs.
- During the MAcTEmPo project two key future research topics were identified. The first relates to diffuse emissions from urban metal stocks which will be investigated in a PhD-thesis at TUW.IWAG. The second identified research topic involves integrating the science of MFSA with the policy world. TUW.IWAG has been awarded funding to conduct a project titled: Material Flow Analysis as a Tool for Resource Policy Making. This project aims to examine the links between the results of MFSA and policy decision making processes on a case study basis.

Policy Strategies

- Using MFSA for policy making involves shifting from the back-end so called „filter strategies“ to more pro-active front-end measures which look holistically at the design of goods, services and regions.
- MFSA is a complementary tool to traditional environmental and resource management strategies. Today’s environmental monitoring systems measure the current state on the environment and tend to focus on single issues with little consideration of the total system. MFSA should be used as a environmental decision making tool since it can present a holistic picture of the system linking current information and data bases. Furthermore, MFSA focuses on short and long-term loadings and highlights current and potential stocks.
- In order to reduce resource depletion and environmental harm, materials (including goods and substances) must be used within the anthroposphere in an optimum manner. MFSA provides a guiding tool for efficient resource management within the anthroposphere. Decision makers responsible for a given system, here the City of Vienna, can use the results from MFSA studies to examine the potential effectiveness of their policies both within the anthroposphere and in relation to the environment.
- A comparison between the Vienna Case study with other investigations reveals that in some cases traditional national or EU-wide environmental standards should be combined with regionally adapted environmental protection and resource management strategies. This recommendation is primarily based on the fact that the dilution potential of environmental sinks and conveyor belts, as well as the availability of resources is regionally variable.
- To assess the sustainability of urban metabolism geogenic references can be used. Such a comparison could indicate the „gap“ between today’s metabolism in relation to geogenic (prior to settlement) reference conditions. Sustainable (efficient) resource management should be defined in the sense that anthropogenic material flows into the environment strive towards achieving geogenic references. The results of MFSA studies provide a useful platform for discussing different management strategies in view of this goal.
- It is necessary to explore how MFSA can be utilised in the „real world“ and what form/type/level of information is most useful for policy makers. A number of controlled experiments on the enterprise, urban and regional scale should therefore be conducted. This strategy is essential since new methods and additional data does not necessarily lead to improved policy making. With the experience of a number of controlled experiments the capacity of efficient implementation of MFSA in the policy world will rapidly increase.
- The real potential of MFSA will be achieved when resource managers (MFSA-experts) work in conjunction with the social sciences and policy makers to determine the most efficient materials management scenarios. Then, the effects of social, technical and economic tools (education, taxes, legislation, materials accounting systems, cost benefit analysis etc.) on materials flows can be discussed in view of achieving sustainable materials management.

Overall Conclusions and Recommendations

- Future environmental policies should be expanded from measuring the human impact on environmental media to designing efficient resource management strategies with the main emphasis on the anthroposphere.
- The strategy to control the anthropogenic metabolism based on Material Flow and Stock Analysis (MFSA) is complementary to traditional environmental and resource management strategies.
- Decision makers responsible for a given system should use MFSA as a base to examine the potential effectiveness of their policies both within the anthroposphere and the environment.
- The current investigations into the use of MFSA have been primarily academically focused. However, experiences show that the tool has a significant potential for use in policy making. MFSA requires further capacity building. In order to broaden the experience and use of MFSA, a number of controlled experiments on the enterprise, city and regional scale should be conducted. In addition, MFSA education programs should be implemented.

5 Collaboration

- Exchange of personnel: In October 1997 Richard Obernosterer spent two weeks at ULIN.TEMA.WE in Linköping, Sweden to discuss topics on the urban metabolism.
- Daniel Janett of EAWAG.RWM collaborated with TUW.IWAG to develop a questionnaire for analysing practical experiences with the application of MFSA in the past.
- αn additional project financed by the City of Vienna was conducted by TUW.IWAG [Paumann et al. 1997] which compared the results of the anthropogenic metabolism of the City of Vienna with the natural metabolism of the regional biosphere.
- In order to investigate better the use of MFSA for the political decision process, an additional research proposal of TUW.IWAG has been developed together with the Chair of Political Science in Salzburg, Austria. This project has been accepted by the Austrian Science Research Foundation for funding.

6 List of Publications

6.1 In press

Hendriks, C., Müller, D., Obernosterer, R. & Brunner, P.H. (1998) *Material Flow Analysis: A Tool to Support Environmental Policy Decision Making*. Proceedings to the Third International Expert Seminar on Environmental Management Instruments "New Public Management of Natural Resources" in London, International Council for Local Environmental Initiatives (ICLEI), Freiburg.

Paumann, R., Obernosterer, R. & Brunner, P.H. (1997) *Wechselwirkung zwischen anthropogenem und natürlichem Stoffhaushalt der Stadt Wien am Beispiel von Kohlenstoff, Stickstoff und Blei*. Institut für Wassergüte und Abfallwirtschaft, Abteilung Abfallwirtschaft, TU Wien, Wien.

6.2 Published

Brunner, P.H. (1997) *Material Flow Analysis - a Tool to Support Decision Making in Wastes and Resources Management.* In: Proceedings of ECO-INFORMA '97. Hrsg. Alef, K. et al., Eco-Informa Press, Altendorf/Bamberg, Deutschland, p. 374-380.

Daxbeck H., Lampert Ch., Morf L., Obernosterer R., Rechberger H., Reiner I. & Brunner P. H. (1997) *The Anthropogenic Metabolism of the City of Vienna*, Proceedings of the ConAccount workshop 21-23 January, 1997 Leiden, The Netherlands; Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability, In: Wuppertal Special 4, Wuppertal Institute for Climate, Environment and Energy, Germany, ISBN 3-92 99 44-05-7, p. 247 - 251.

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Obernosterer, R. & Brunner, P.H. (1997*) Baurestmassen als zukünftig Hauptquelle für FCKW in der Abfallwirtschaft.* Müll und Abfall, 2/97, p. 89-95.

Obernosterer, R., Daxbeck, H., Gagan, T., Glenck, E., Hendriks, C., Morf, L., Paumann, R., Reiner, I. & Brunner P.H (in preparation 1998a*) Urban Metabolism - The City of Vienna; Materials Accounting as a Tool for Decision Making in Environmental Policy.* 4th European Commission Programme for Environment and Climate. Institute for Water Quality and Waste Management, Vienna University of Technology, Vienna.

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Paumann, R., Obernosterer, R. & Brunner, P.H. (1997) *Wechselwirkung zwischen anthropogenem und natürlichem Stoffhaushalt der Stadt Wien am Beispiel von Kohlenstoff, Stickstoff und Blei*. Institut für Wassergüte und Abfallwirtschaft, Abteilung Abfallwirtschaft, TU-Wien, Wien.

ANNEX 2 TO SUMMARY REPORT
Report of the contractor LIU.TEMA

URBAN METABOLISM
Metals in Stockholm

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1 Objectives

The *overall objectives* of the research activities have been to provide a scientific basis for evaluating the present state of the urban environment, future risks and the need for remedial measures - according to heavy metals. A first part of this project was focused on collecting information about flows and stocks of metals in Stockholm in the data base *Stockhome*. The time period studied was the 20th century and the metals chosen were cadmium, chromium, copper, lead, mercury, nickel and zinc. In a second part of the project, flow schemes and a flow model were to be constructed that synthesise flows and stocks in the anthroposphere. The model should be a tool for scenarios of environmental impact for different measures.

The objectives have been to present the data base Stockhome and to use it as a platform for the model mentioned above. The model would serve as an interface to the metal data, allowing e.g. graphic display, overview and simulation. Hence the model should be based on concepts which are familiar to e.g. a decision maker, or useful in educational context. One objective during the reporting period was to find a basic concept and model structure in which all collected data could be entered. However, all collected data in the model is more or less uncertain. Thus, another objective was to find ways to manage these uncertainties.

Further, the consumption emissions from the use of various goods were to be calculated within the model. This should be done from emission factors, given in the literature, and the inflow of goods to the anthroposphere. The consumption emissions were to be calculated for the 20th century, providing assessments of emissions from different sources. Finally, the model should facilitate the evaluation of scenarios for the next decades.

2 Methodology/Approach

2.1 Definition of system boundaries

The research was done as a case study covering the flows and accumulation of heavy metals from 1900 up to 1995 in the anthroposphere of the Swedish capital Stockholm. The administrative border of Stockholm City was chosen as spatial system boarder. The work focused the urban metabolism of the metals cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni) and zinc (Zn). This includes the calculation of metal flows and stocks in various goods for different time periods. Further, emissions from these goods to the environment have been roughly calculated. Corresponding flows and stocks within the environment were excluded in this study. However, Stockholm is a study object in the research programme ”Metals in Urban and Forest Areas” (the Swedish Environmental Protection Agency). Here, consumption emissions are analysed in relation to present metal flows in storm water, sewage water etc. or to present metal stocks in soils and sediments.

2.2 Data base

In order to map the flows and stocks of heavy metals in the anthroposphere of Stockholm, data has been collected for the total amount of metal used during the 20th century. Official statistics on a national, regional and local level were used and contacts were established with industrial/sector representatives from production/construction/authorities in order to calculate flows and stocks of the different metals. The number of information sources and the total data presented constitute a most comprehensive data base. Thus, data has been collected for:

- total amount of metal used during the 20th century
- total amount used today
- the present net inflow

using the following methods:

- Scaling down from national statistics
- Life span of various goods * average consumption per year
- Metal content per good
- Information available from e.g. from the industrial or official sectors.

All information about flows and stocks in the Swedish model is more or less inaccurate. Traditionally an uncertainty interval may be written as X $\pm$Y. Here, the use of magnitudes turned out to be more practical at large uncertainties, e.g. "probably X but maybe as much as 3*X or as little as 1/3 *X". To describe these magnitudes we have used the notation X */Y. The magnitudes were classified in levels from 1 to 5:

Level	Magnitude
1	*/ 1.1
2	*/ 1.33
3	*/ 2
4	*/ 4
5	*/ 10

As the data base is close linked to a flow model, further details are discussed below. See also Lohm et al. (1996 and 1997) and case study report ”Metals in Stockholm”.

2.3 Flow model

The model should support "natural science" discussions, e.g. flows and stocks of substances with its laws of mass conservation, empirical assumptions about emissions etc. It should support "social science" discussions including contexts of importance for management of goods as well as "economical" discussions regarding the values creating the forces behind the consumption processes. Furthermore, it should allow for "political" discussions, e.g. information and knowledge trading for policy formulation.

Since the model should be good enough from several viewpoints, compromises have been done. The system boundary is city of Stockholm, but the landfill outside Stockholm is included in the model as are also waste-water flows emanating from areas outside the city border. The hibernating stock is used in the model despite definition vagueness and validation problems. The model structure does not consider spatial conditions, the design and implementation of large technical systems (infrastructure) and so on.

Collected data consists of amounts of heavy metal contained in different goods. For several goods data also includes historical information, some cases have year to year precision but most however only the time periods when the use was most intensive. To get "on top" of the information, and to get a viewpoint for further discussions, a computer model was created.

The purpose of the computer model was to allow for materials accounting — a view of flows and stocks with graphical presentation. Furthermore fast access to data, summary of references, categorisation of goods according to different aspects of use and management in society should be supported.

The structure of the model was chosen to illustrate the entire consumption process of heavy metal containing goods in an urban area, also including collection of worn-out goods as well as the emissions, leakage, of metals to the biosphere. A flow diagram is shown in fig 1.

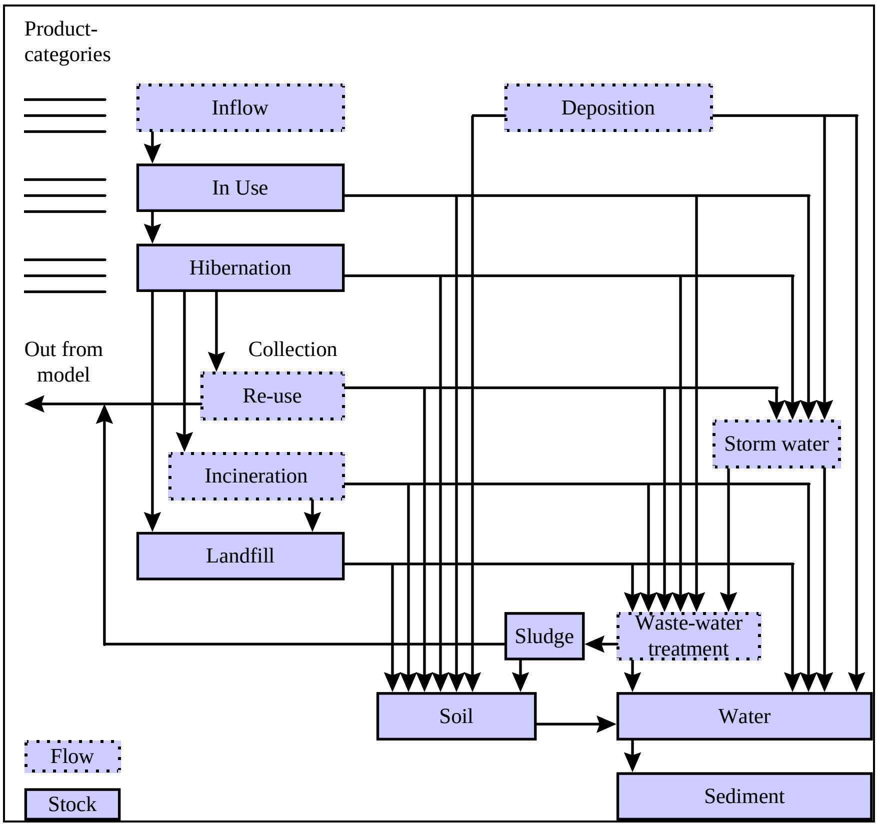


Figure 1. Model structure.

The upper left part is related to the use of goods, the lower left part the management of wasted goods and the right part corresponds to leakage of metals during use and waste management. The definitions of the sub-processes are as follows:

Inflow. Flow of different kinds of goods containing heavy metals to the urban region, i.e. Stockholm city.
Only the quantity of goods used in the region will be considered. E.g. a power cable imported to a dealer in the city to be cut, re–packed and sold in smaller quantities to customers outside the region is not included.

In use. The stock of a good which provides the service it is made for.
The use may generate an emission of heavy metal.

Hibernation. The stock of a good which no longer provides the service it is made for.

E.g. a cable which is no longer in use but still left in the ground will be considered as hibernating. Hibernation may also generate an emission of heavy metals. Hibernation may be subject to a considerable uncertainty, since all goods that “disappear“ out of control are considered to be in Hibernation (i.e., all that is no longer In use and is not transferred to Collection).

Re–use. Flow of goods out of the scoop of model, i.e. goods that are not anymore considered to be a part of the consumption process within Stockholm city.
Re–use means additional use of the used goods, or additional use of the substances in the goods. The management may generate an emission. Re–used amounts may be re–input again via Input as new goods.

Incineration. An important part of the waste management is incineration, often utilising the energy in wasted goods for co-generating electricity and heat. Ashes from the incineration plants are deposited in landfills.
At incineration the energy in the wasted goods is “re–used“. Also this management may generate an emission.

Landfill. When having reached the landfill, the metal has reached its lowest societal value in the consumption process and is not anymore subject to human activities such as utilising, intermediate storage, transports or refining. In the society’s perspective this is the ”end station” of goods, however emissions may occur.

The model was implemented in Microsoft Excel. To the general comments on this choice it could be added that Excel seem to be widely diffused around the world, there is a knowledge of how to use and modify Excel spread-sheets and that costs for future support of the model hence will be reduced.

MacTempo focuses the "tool" aspect of material flow analysis, with respect to decision support and policy formulation. This may be interpreted in a way that supports ”indirect” use of MFA, i.e. MFA is performed by scientists and the ”results” are communicated to decision makers. However, considerable pedagogic advantages are obtained if the MFA would be communicated as a tool itself, for direct use, by decision makers. Not only software supported analyses would be carried out, but also a long term maintenance of the database, model features and presentation interface.

Could this be achieved, or facilitated, by a transparent model design and a choice of easily available hardware and software platforms, the knowledge trading from research to practical use would be significantly faster, creating more welfare values, be of high societal relevance and one obstacle
in the mission of realising "living MFA" would be removed.

The interface of the model is, basically, the flow diagram itself, and a choice of different contexts to be viewed. See figure 2.

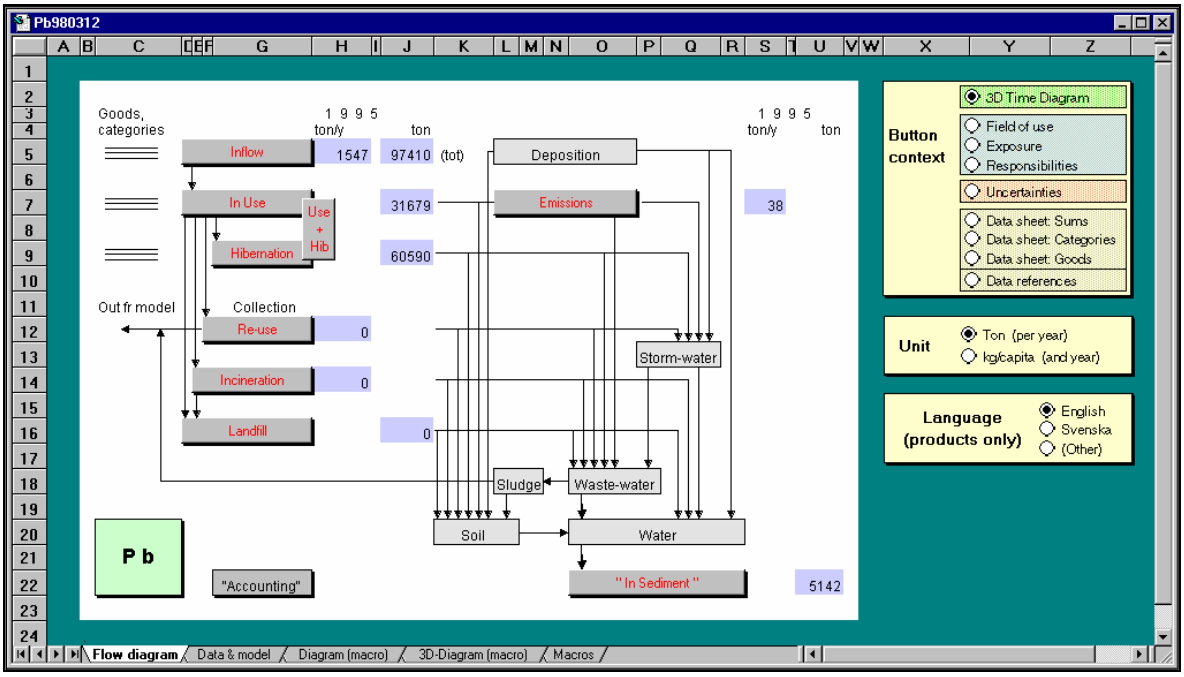


Figure 2. Interface of the model.

For an inexperienced user, the easiest way to use the model is by using the context sensitive buttons in the flow diagram (i.e. buttons only appear when they have a function).

To see numerical data, the alternative “Data sheet, goods” is selected. The numerical data is organised in rows with goods, and in columns with time periods. Metals from several goods with similar characteristics may be gathered together into good categories. And also, only the total sums may considered where all metal in goods is summed together.

Time periods in the model are coarser in the beginning and finer nearer present time. The first time periods, from 1900 to 1970 are in ten-year steps, from 1970 to 1985 with five-year steps, and from 1985 to 1995 with one-year steps. See figure 3, where data are displayed on a good category level.

7	Flow diagram	Inflow			Refs		3D Time d	Time diag	?		Field of use		Exposure		Responsib			Uncert					
8	Inflow	10 year periods							5 year periods			1 year periods										1995	
9	ton/y	00-09	10-19	20-29	30-39	40-49	50-59	60-69	70-74	75-79	80-84	85	86	87	88	89	90	91	92	93	94	95	unc
16	Cable Power & pl	5,761	3,471	241,1	268,5	558,8	564,1	556	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	0,302	3
21	Accumulators	0	0	0	0	0	286,1	844,1	1281	1341	1272	1717	1613	1680	1774	1716	1659	1233	1256	1302	1302	1302	3
25	Tube and pipe joi	75,57	48,98	130,8	247,7	158,2	224,3	110	3,88	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	PVC	0	0	0	0	0	0	0	22,37	22,37	22,42	22,43	22,43	22,43	22,38	22,38	22,38	22,37	22,37	22,37	22,37	22,37	3
34	Building preserva	0,04	0,04	0,04	0,04	77,37	193,4	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	3
37	Public	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,583	2,9
42	Vehicles & boats	0	0	0	0	9,5	85	152,5	294,4	280,9	132,2	80	71,5	62,6	49,1	48,5	40	21,9	32,1	18,4	12,4	12,4	2,8
52	Household & hob	5,354	5,354	5,354	5,354	5,354	65,35	65,35	65,95	66,85	68,65	69,85	69,85	69,85	69,85	69,85	69,85	69,85	69,85	69,85	69,85	69,85	2,9
55	S u m	89,31	60,43	379,9	524,2	811,8	1421	1731	1670	1714	1498	1892	1780	1838	1918	1860	1794	1350	1383	1416	1410	1410	

Fig 3. Example of numeric data in the Pb-model.

Sooner or later the large amount of numeric data will cause a demand for references, especially to evaluate the quality of the numeric data. References are indicated by accessing the Empirical data (inflow) area in the model and then pointing at a cell with the cursor. A cell note sheet will then appear, with a hint on the reference. Due to space limitation only a raw reference and sometimes some basic assumptions are revealed on the cell note — further details and additional discussions regarding the reference are to be found in Lohm et al. (1997). An example of this is seen in figure 4.

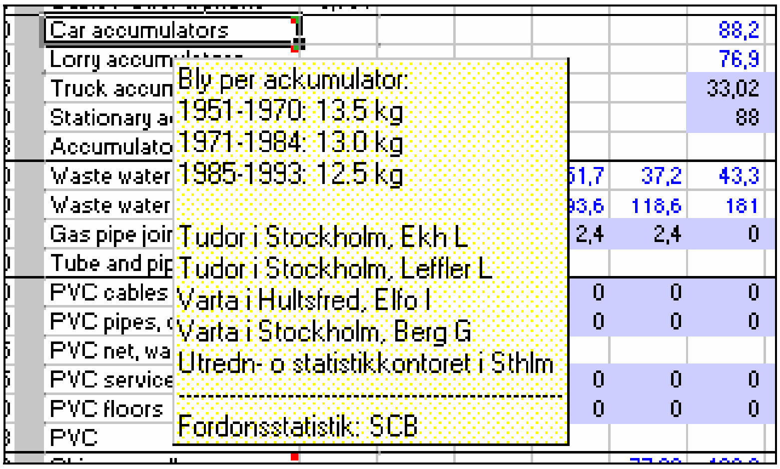


Figure 4. Cell note refs. for car accumulators.

A sort of numerical estimation of the uncertainties of each good category may be seen with the Uncertainties context selection. See figure 5. Remark that the uncertainty calculations does not have support from theoretical statistical theory, because of e.g. too few data, subjective (interviewed data), extremely vague data and possibly non-independent data. See the discussion in detailed case study report and Lohm et al. (1997) for more details.

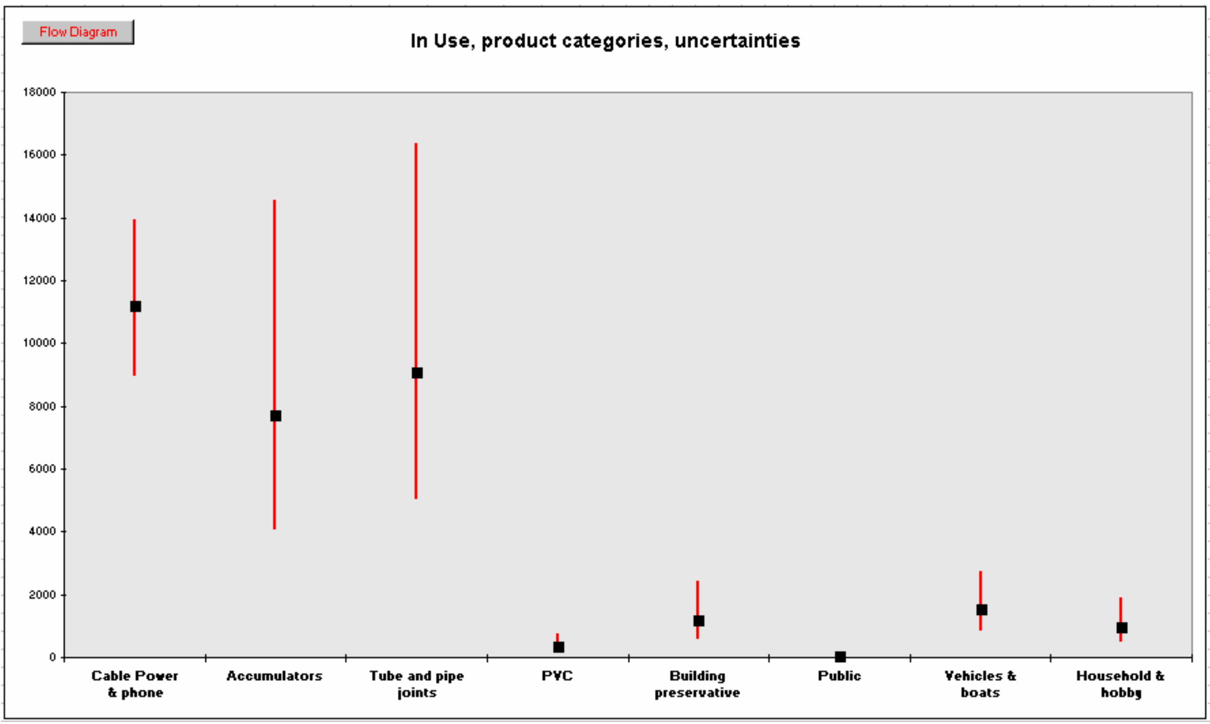


Figure 5. Uncertainties for Pb good categories.

Indications of the data quality may hence be found in the column right of year 1995 and in the cell notes (type of references) for each product, as well as in the Uncertainties diagram for categories.
Though the numeric data fields make all facts available to the user, it is not a convenient presentation for creating an view over the metal flows and stocks. For this purpose the diagram contexts in the flow charts could be used. The time diagram for e.g. Inflow displays historical trends, and may look like the example presented in figure 6.

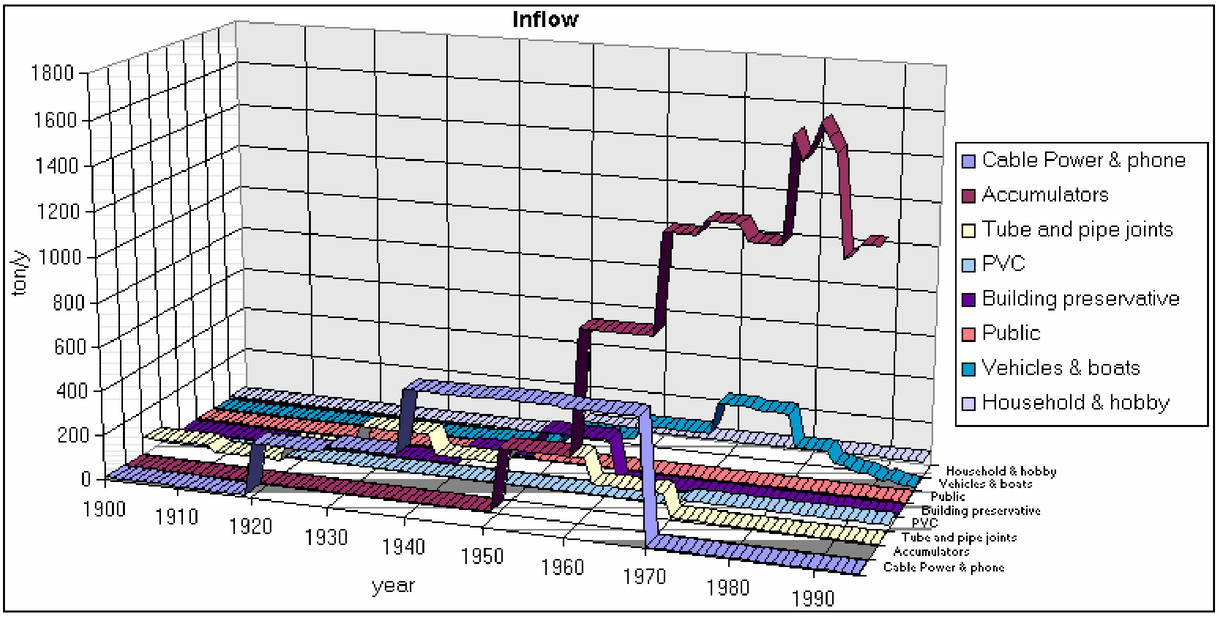


Figure 6. Time diagram, Pb inflow (ton/yr).

So far in this discussion the model has had a “natural science” perspective, with mass flows and stock as the modelled object. However, to be more useful in a social science or policy formulation perspective, there are also other viewpoints for the data. See figure 7. One is the issue where in society the metals are used. This issue may be addressed by the context Field of use, and gives a distribution of the 1995 situation on the categories Infrastructure, Buildings, Household, Enterprises and Vehicles.

Another issue is the exposure for corrosion, i.e. the degree to what different goods leak metals to the biosphere. This context is called Exposure, and gives the distribution on the conditions In Soil, In Water, In Air (outdoor), and In Protection (indoor, or no leakage conditions).

The third issue is who are responsible for the management of metal-containing goods. The context is called Responsibility, and maps metals on Individual or Collective categories.

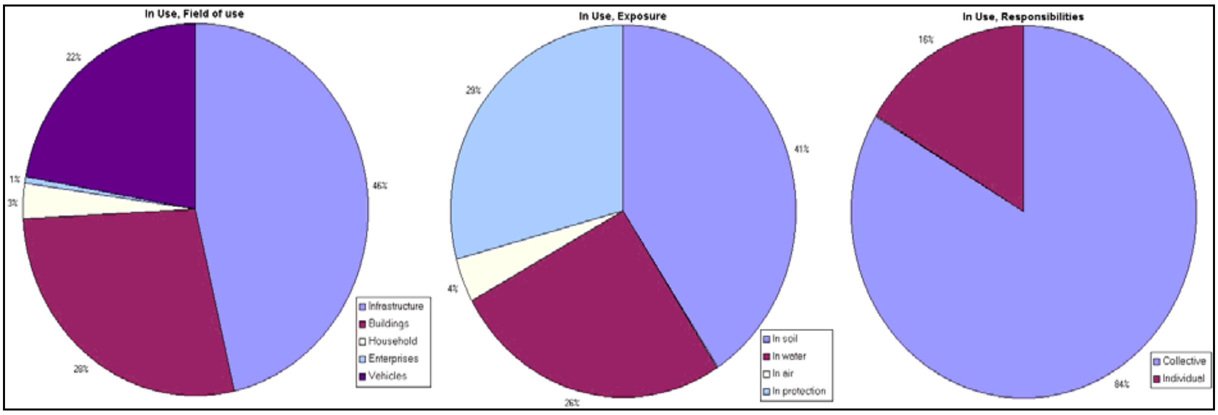


Figure 7.
Example of categorisations. The figure is made from three different diagrams from the Pb model.

These pie charts are examples. Other categorisations would be availability (cost for collecting for re-use), replace ability (to replace with goods made without heavy metals), exposure to human beings (goods or emissions), health risks for human beings etc. The technique with categorisations leave open also for future ideas and analyses.

During the project the concept of “accounting” has been discussed. With the supporting economical metaphor the flows and stocks *in the society* may be described as in fig 8 (in kg per capita). The upper bar diagram is the flows, where the Inflow dominates, the Recycling and Incineration flows are zero due to lack of data (to be included for the final version). The Emissions flow indicates the small flow out of the system (society). The Net Profit is the increase in the amount of lead in InUse that year. The lower bar diagram shows the “accounts” — the accumulated amounts of lead since 1900. The largest account are Hibernation, possibly because the Recycling and Incineration flows are not included in the calculation, and the “lost” lead is contained in there.

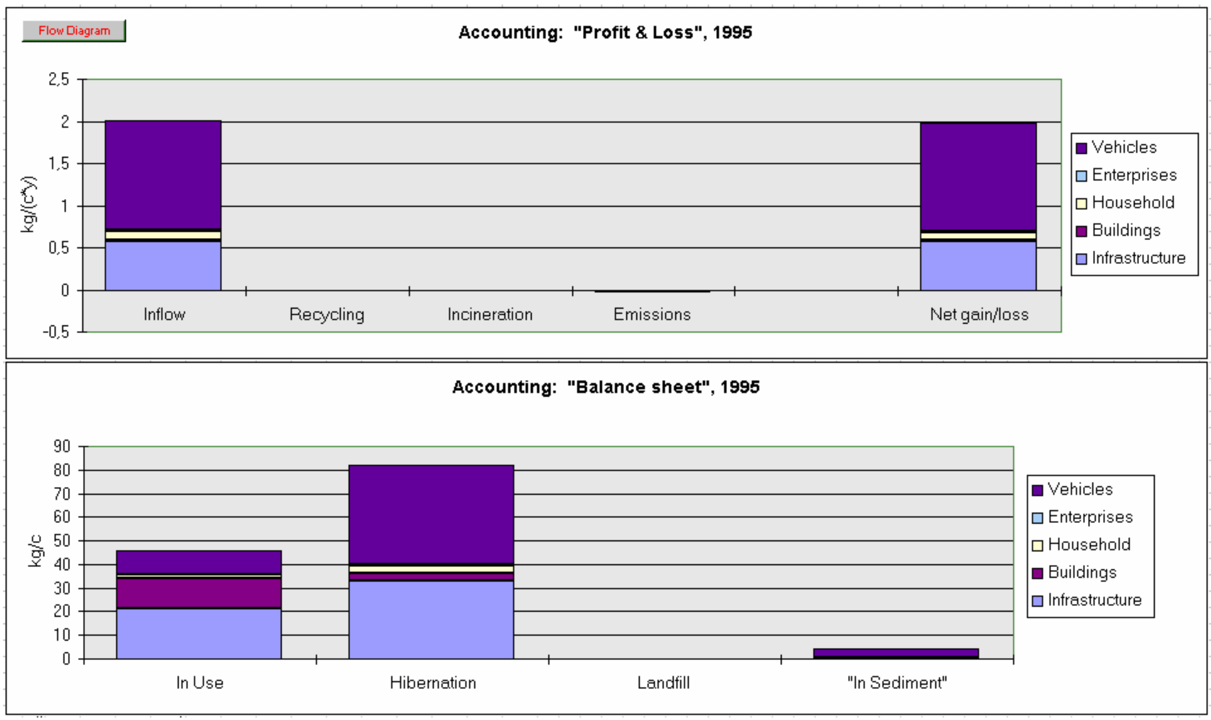


Figure 8. "Materials Accounts" from the Pb model. Note that recycling data not included.

To illustrate the flexibility in presentation, the diagrams are focused to "Field of use" and a "Per capita" presentation. One indication from the diagrams is that there is a large present inflow of vehicle lead (accumulators), but the stocks contains a lot of infrastructure lead (power cables, pipe joints). The accounting presentation makes possible the discussion "what is large, what is small".

2.4 Consumption emissions

Consumption emissions of metals from the use of various goods may be calculated by the model. Here, a simple approach with emission factors mainly from Tarr & Ayres (1990, The Hudson-Raritan Basin. In: Turner II et al. (eds.). The Earth as Transformed by Human Action. Cambridge University Press, New York) and the net inflow of a metal to the anthroposphere per time period has been used. These emission factors give the proportion of a metal in a specific good that will be released into the environment within a decade. In this study, a delay time of 10 years has been used for all type of goods except in case of direct emissions, e.g. lead from petrol. Obviously, this is a simplification as the release from a good often is slow and may go on for more than one decade.

Note that calculated consumption emissions per decade from specific goods, represent the total amount of metal ever released from this specific use. Clearly, these calculations are most uncertain and the results give more a hint of the magnitude of potential emissions from goods. See also section 3.

3 Main results obtained

Results from the use of the data base and the flow model are here briefly presented. For a more detailed presentation of the data base Stockhome - see Lohm et al. (1997) and case study report "Metals in Stockholm".

For some metals, e.g. cadmium, lead and mercury, the statistical sources of historical consumption allow us to follow the development over time for the 20th century. For other metals, e.g. chromium, copper and zinc, the historical consumption has been roughly estimated. Some examples are shown in figures 9 -10.

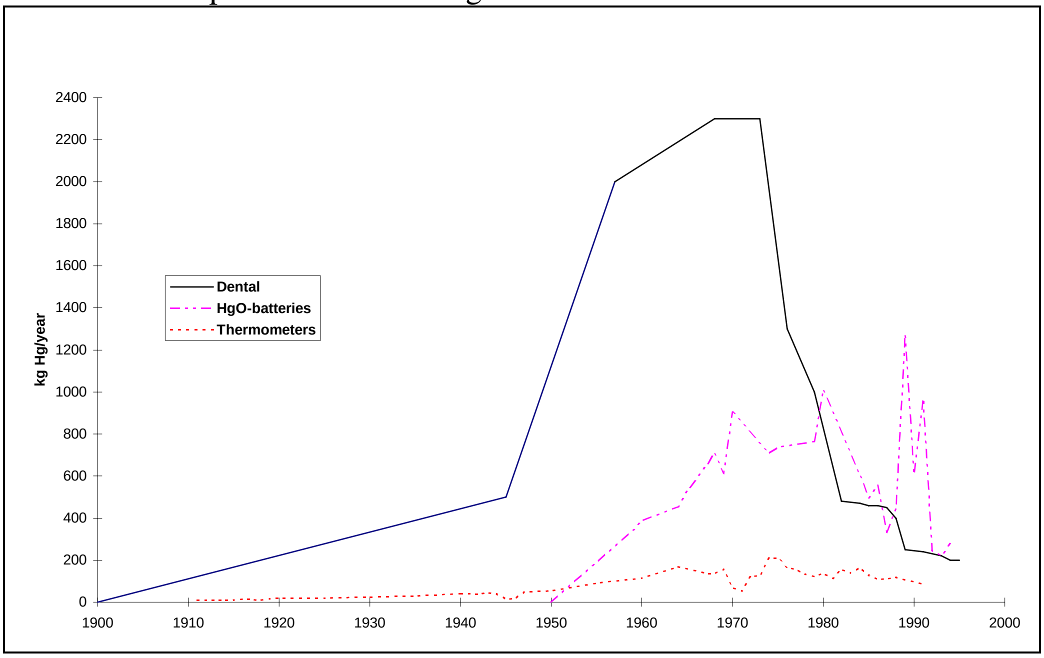


Fig. 9 Consumption of Hg (kg/year) in Stockholm for major uses, 1900-1995.

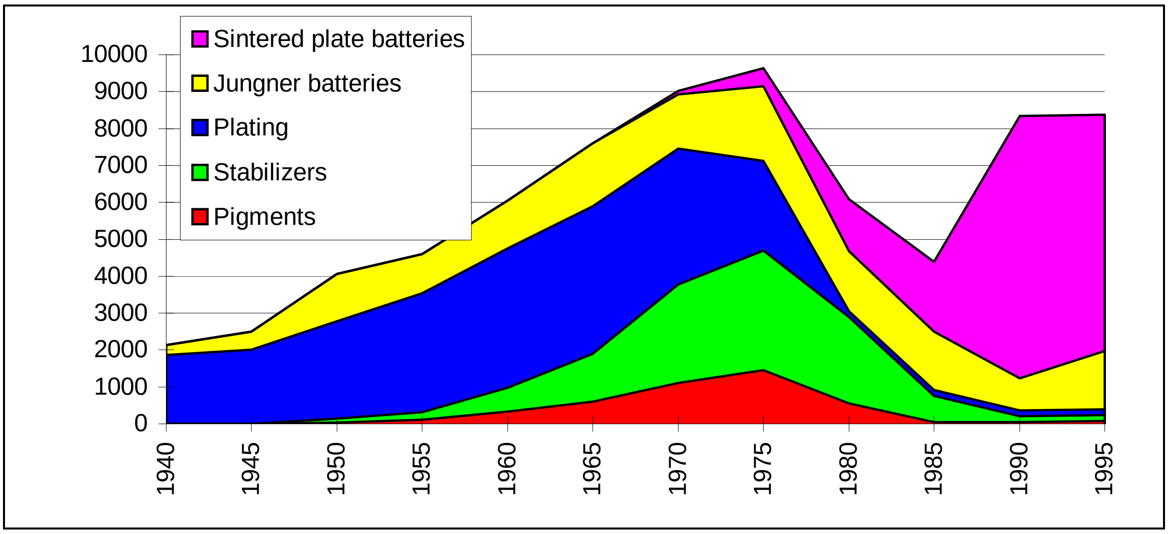


Fig. 10. Consumption of Cd (kg/year) in Stockholm for major uses 1940-1995.

The stock of metals in Stockholm has been calculated, see table 2.

Table 2. Stock 1995 (tonnes or kg/capita) and inflow 1995 (tonnes/year or kg/capita and year) of metals in the anthroposphere of Stockholm.

	Stock , 1995 (tonnes)	*Stock, 1995 (kg/capita)*	*Inflow 1995 (tonnes)*	*Inflow 1995 (kg/capita)*
Mercury	7	0.01	0.5	0.001
Cadmium	120	0.2	9	0.01
Nickel	2 500	4	190	0.3
Chromium	5 500	8	350	0.5
Zinc	29 000	40	1 900	3
Lead	47 000	65	1 500	2
Copper	120 000	170	1 500	2

Every metal stock has also been divided into different categories - sector of use (household, infrastructure, buildings, vehicles, industry) and degree of exposure (air, water, soil, protected).

For lead, nearly 50 000 tonnes are in use today in various goods. Approximately 40 000 tonnes are exposed to corrosion in a varying degree. For the other metals the corresponding figures are - cadmium 120/40, copper 120 000/40 000, chromium 5500/2500, nickel 2500/700 and zinc 30 000/20 000. A mercury stock of 7 tonnes is totally dominated by the use of dental alloys.

For this annex to the MacTempo summary report, lead has been chosen as an example. The distribution of lead in some goods on different sectors of use is shown in figure 11. As a comparison, the total amount of lead in petrol, consumed during the 20th century in Stockholm and now accumulated in soils/sediments, has been included.

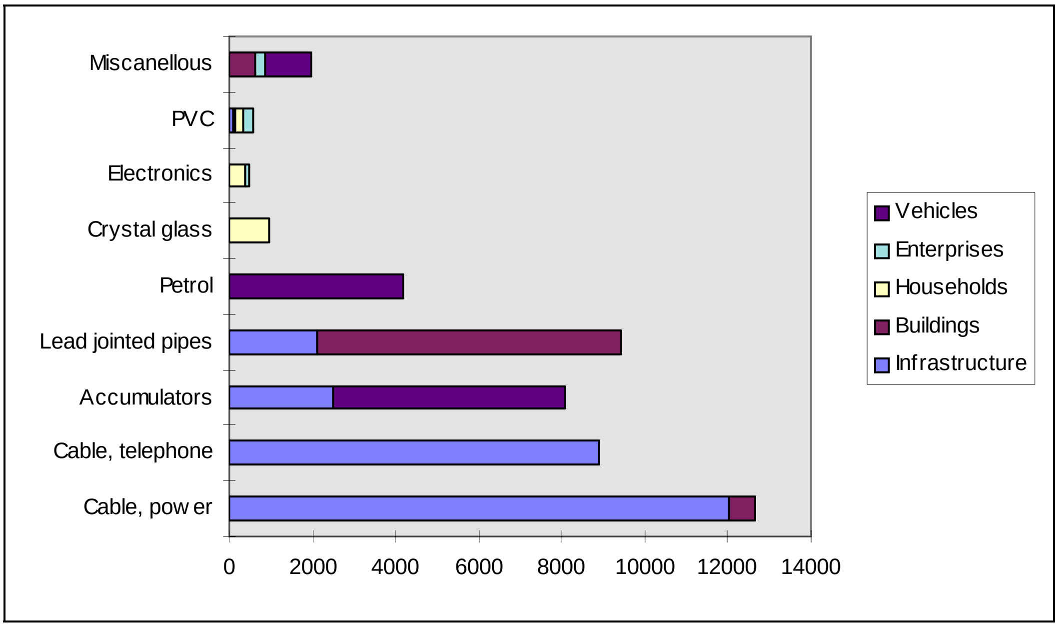


Figure 11. Stock of lead (tonnes) in various goods, Stockholm 1995 distributed different sectors.

From the Pb inflow per time period (see figure 6) the consumption emissions from various goods were calculated according to the simple method mentioned in section 2.3. For lead, the emissions from consumption of leaded petrol were dominant for the 1960s - 1980s. However, these emissions excluded, the contributions from other goods are better elucidated, see figure 12.

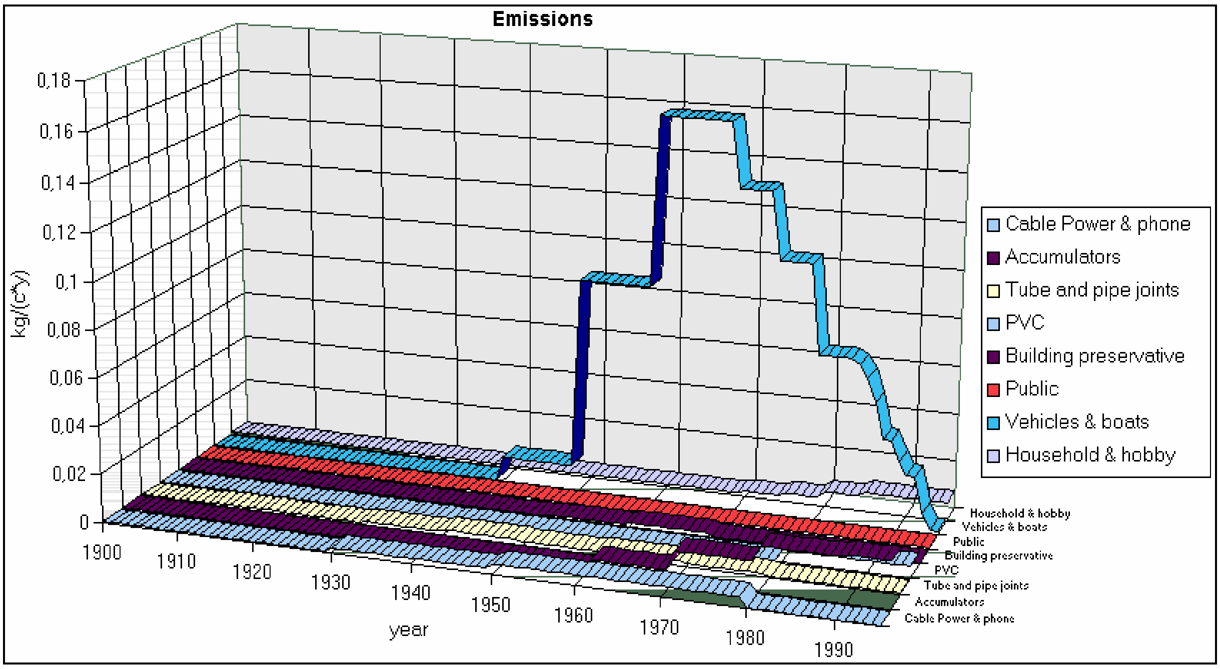
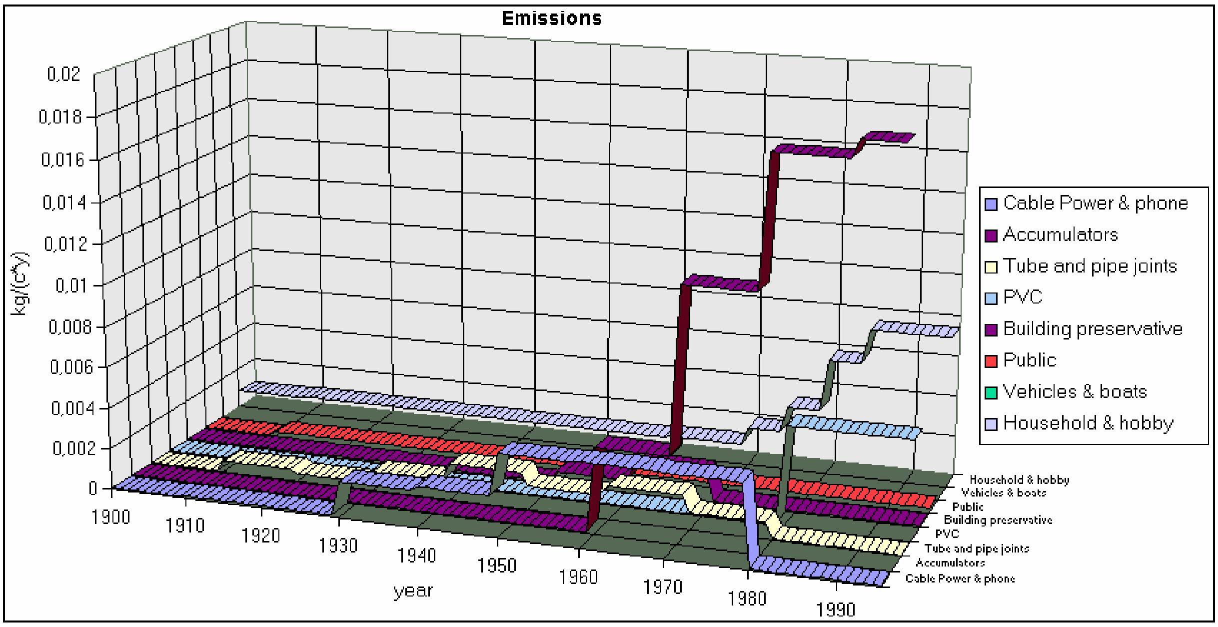


Figure 12. Calculated consumption emissions of lead from different goods (kg/year and capita), Stockholm 1900-1995.



(Lead in petrol excluded)

Figure 12: continued. Calculated consumption emissions of lead from different goods (kg/year and capita), Stockholm 1900-1995.

Obviously, the consumption emissions from goods with a long life-time, e.g. lead-shielded cable, will continue to release lead even after 10 years. Thus, the emissions in the 1990s from cables are not zero as indicated in figure 12. However, our model is also prepared for a more sophisticated approach for calculation of consumption emissions. Data is available for the parts of the stock that are exposed to different corrosive environments, i.e. exposed to corrosion in water, soil or atmosphere. The part of the stock that is protected to corrosion, mostly indoor goods, is also given in the data base Stockhome. From the amount (or surface area) of a specific good in a specific environment, the consumption emission may then be calculated by empirical corrosion factors. These factors are now being developed by the Swedish Corrosion Institute in long time exposure experiments.

From the simplified method of calculation, given by Ayres (c.f. 2.4), indications of major emission sources per metal may be given as a first approximation, see table 3.

Table 3. Major sources for consumption emissions from metal containing goods.

Metal	*Goods*
Cadmium	zinc surfaces, vehicles
Chromium	pigments, concrete
Copper	roofs, tap water system
Lead	accumulators, cables
Mercury	amalgam
Nickel	stainless steel
Zinc	galvanised steel

Obviously, the focus should be on goods with a large stock e.g. zinc surfaces, copper in roofs/ tap water systems or lead in cables. But, even a minor stock will be of prime environmental importance if the ”emission/ corrosion factor” indicates a high release per unit, e.g. chromium pigments.

4 Discussion and conclusions

In Stockholm, high, sometimes extremely high, concentrations of cadmium, lead and mercury have been found in sediments, soils and ground waters (Bergbäck & Johansson, 1996). The local authorities are now, together with Linköping University, analysing connections between the stock of metals in the anthroposphere and these high environmental loads (see figure 1).

With the data base/ flow model approach from this MacTempo case study, there has been an intensive *co-operation with the Local Environmental Government in Stockholm and with the Swedish Environmental Protection Agency*. From this work it can be concluded:

It is possible to *reconstruct the stock* of goods even for a long time period. Here we have shown that the accumulation of metals in goods is most extensive. The emissions from the anthroposphere of Stockholm are so far small in relation to the stock. Thus, most

environmental concern should be directed to *manage the stock* in order to minimise future environmental impact. Further, older areas of use often dominate the stock for goods with a long ”life expectancy”. Some of the goods, e.g. ”dead cable”, are today forgotten, and the responsibility for the good is unclear.
This approach gives possibilities for *pre early recognitions* which is more *pro active* instead of *re active*.

In the discussions mentioned above, the need of a *data base that could be generalised* to other urban areas was stressed. Obviously, this generalisation is a prerequisite to include the Hinterland, both in terms of emissions (drainage areas, sewage treatment plants and waste) and metal resources.

There was also an agreement that *environmental indexes* could be extracted from the data base/ model. These indexes should be based on the use of material rather than based on the state of the environment. So far, the model gives management of metal-containing goods in *individual or collective responsibilities*. However, this could easily be extended to e.g. *responsibilities for different branches or the private sphere contra public services*. For example, a typical question for the Local Environmental Government in Stockholm to address is how to give licence for demolition work.

The *pedagogic advantages* with the data base/ model were discussed. There is a challenge to increase the awareness of the potential environmental impact from metal stocks in the anthroposphere. This could be done, beginning in school, i.e. with an Internet interface. The Local Environmental Government is most concerned to have an interactive work with our model linked to other data bases in the local Agenda 21 programme. This work will be intensified during 1998.

The work so far will form a platform for further development. The structure of the model (see figure 1), primarily designed for “physical” metal flows and accumulations (ton/year and ton of metal), also turns out to support a *value analysis* for a good during the consumption phases, see table 4. Domains for value analysis could be e.g. economical values, utility values, toxicity, substitutability, availability, material values (also energy) and costs for final deposition.

Table 4. Example of some values and costs for a good.

Sub-process	Positive value	Negative value
Inflow	Economical value (potential for use)	
In use	Utility value	
Hibernation	Material and energy value.	Cost for extraction Cost for transport, collection
Re-use	Material value	(maybe negative rest value)
Incineration	Energy value	
Landfill		Cost for landfill

Extraction cost may be the work to get a water pipe out of a concrete wall, or digging a power cable out of the ground. Simpler it may be carrying an old TV down from the attic. It is evident that a considerable change in the value of a good occurs between In use and Hibernation. From having had a large positive utility value the value drastically decreases so that the material and energy values may not cover the costs for collection. The good is then most likely left where it is.

In this MacTempo case, study tools for decision makers in environmental protection have been implemented through

- a *data base* ”Stockhome” giving changes in metal flows and stocks in a long time perspective. The present stocks (1995) are divided in sectors of use, degree of exposure to corrosion and in areas of responsibility for the goods. The data base will be further developed in co-operation with the Local Environment Protection Government of Stockholm.

- an *excel base, ”flow model*”, to calculate consumption emissions with different methodology. In order to assess environmental impact of metals in various goods, the potential release of metals must be estimated, even if the calculations are uncertain.

Through the data base and the model, anthropogenic metal flows/ stocks can be analysed in relation to natural flows/stocks in order to answer questions like
What goods can/must be accepted per metal?
What recycling rates must be achieved in order not to exceed natural flows?

Thus, with these tools, there are possibilities to assess metal flows and stocks in the anthroposphere in relation to corresponding flows/stocks in the environment. This gives a platform for early recognition of future problems of environmental loadings and to set priorities/ define measures to protect the environment in urban areas.

However, SFA/MFA is not only a policy tool for environmental protection but also a most useful platform for sustainable resource management. Due to metal ore depletion and the high energy consumption of primary production, recycling of accumulated amounts of metals in urban areas becomes increasingly interesting. Obviously, the extraction cost of metals in various applications must be limited in relation to metal market price. In figure 13 roughly estimated extraction costs for lead in some goods have been plotted against the accumulated amounts in the anthroposphere of Stockholm. According to this example, more than 30 000 tonnes of Pb could be ”mined” from the anthroposphere. However, today only 10 000 tonnes are profitable to extract.

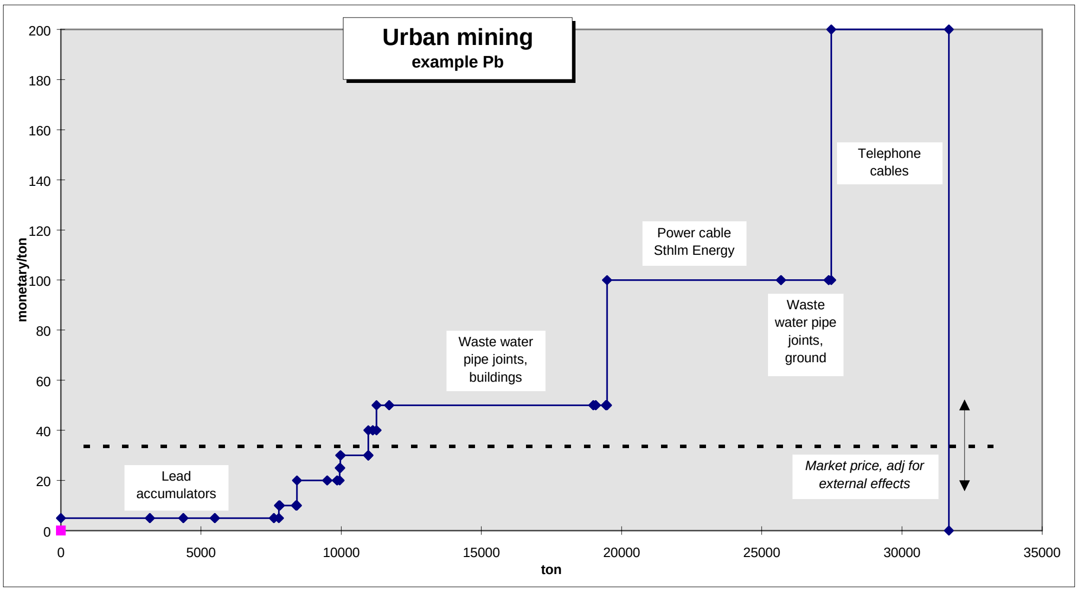


Figure 13.
Assumed extraction cost (monetary units/tonnes) and accumulated amounts (tonnes) for some goods in the anthroposphere of Stockholm. Goods below market price could be subject to urban mining.

Our first analysis reveals that material flux studies allows for the inclusion of different management and policy approaches. From our study it is obvious that environmental issues cannot be fully understood if they are looked at in only an environmental perspective. MFA or SFA is an approach to overcome this. So fare the focus is usually on engineering or applied science but if organisational dynamics could be incorporated the MFA will become a very strong tool regardless which level it is applied.

5 Literature

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Hedbrant et al. *Metal metabolism - few data: How to deal with uncertainties*.

Hedbrant et al. *Empirical analysis of urban mining possibilities*.

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ANNEX 3 to SUMMARY REPORT
Report of the contractor RUL.CML

CHLORINE IN WESTERN EUROPE

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1 Objectives

1.1 General Introduction

Environmental pressure groups are campaigning for a total phase out of chlorine and its compounds, since they are convinced that the environmental risks are too great to be controlled. Industry argues that this is neither necessary, since the risks can be controlled, nor feasible, since 60% of the current production system makes use of chlorinated compounds. Material Flow Analysis (MFA) can give discussions on environmental problems caused by material and substance flows a more factual basis (Udo de Haes et al., 1988; van der Voet 1996a; van der Voet 1996b; Baccini & Bader, 1996). In this study MFA is used to structure and aggregate information on flows of chlorine and its compounds through Western Europe, to identify problem flows and to discuss possiblities to reduce these problemflows.

1.2 Economic importance of chlorine and chlorinated compounds

In the anthroposphere chlorine has come a long way since it was simply a by-product of caustic production at the end of the 19th century. Today chlorine is one of the most important starting materials in the chemical industry. Worldwide production capacity is currently about 44 million tons per year (Müller, 1993). Of the 70,000 frequently used compounds, about 10% contain chlorine. Of these, 99% are organic compounds. Consumers buy chlorine in only a small number of recognizable applications. However, these few applications include the largest single use of chlorine: the plastic PVC, which accounts for about 34% of the use of chlorine in the EU. Some other common consumer applications are (H)CFCs in refrigerators and reactive inorganic chlorine compounds in household cleaning agents. A large number of chlorinated compounds, representing only a small amount of chlorine, are also bought by consumers incorporated in other materials such as dyes and other additives in plastics and pharmaceutical products. All other applications of chlorine occur within the chemical industry as chemical intermediates, or in other branches of industry as auxiliaries, such as chlorinated solvents. In fact, around 60% of consumer products currently contain materials whose production process at some stage involves the use of chlorine or chlorinated compounds.

1.3 Environmental problems related to chlorinated compounds

Since chlorine is of great importance to today’s chemical industry, and the chemical industry is one of the key elements of Western society, it could be argued that the use of chlorine is of great importance to Western society. However, the other side of the coin is that chlorinated compounds contribute to a number of important environmental problems, including: ozone depletion, global warming, toxicity to humans and ecosystems, acidification, smog formation, smell and production of solid waste (Berends & Stoppelenburg, 1990; International Joint Commission 1992 and 1993; Johnston & McCrea 1992; Thornton, 1991; Kleijn, 1993). Two of these problems - ozone depletion and global warming - can be related to a small group of chlorinated compounds: (H)CFCs, Halon 1211, tetrachloromethane and 1,1,1-trichloroethane. The contribution of chlorine to acidification, smog formation, smell and production of solid waste is of minor importance in comparison with other compounds. At this moment the chlorine debate focuses on the toxic effects of chlorinated compounds. From the point of view of environmental management, emissions of intentionally produced and known toxic substances such as pesticides and PCBs are relatively easy to control via bans or restrictions on the applications. Owing to the reactivity and aselectivity of active chlorine, however, unknown chlorinated compounds are produced unintentionally in small quantities as by-products: chloromicropollutants. Thousands of different organochlorines are found in sediments and biota, at least some of these coming from anthropogenic sources. Only a small fraction of these organochlorines can be identified. The uncertainties connected to the environmental impact of anthropogenic chlorine micropollutants are at present a major topic within the chlorine debate (Colborn et al., 1996).

1.4 Objectives and research questions

The main objective of the chlorine case study is to give an overview of flows and stocks of chlorine and chlorinated compounds within the European Union (EU), to identify problemflows, to describe trends and to explore different policy measures and their results. The following subjects were treated:

- goal and systems definition
- inventory of data:
    - ⇒ flows within the industry on the basis of the literature survey
    - ⇒ applications of chlorinated hydrocarbons extrapolated from national data
    - ⇒ emissions extrapolated from national data
- combine these data to get a total overview of flows of chlorinated hydrocarbons through the anthroposphere from the cradle to the grave
- elaboration of the problemflows from stocks of PVC and CFC in the anthroposphere
- describing possibilities to cope with the problem of chlorinated micropollutants
- discussion of policy implications and possible abatement measures

1.5 Case Study Region: Western Europe

By choosing the region one of the most important system boundaries is defined. The chosen region for the chlorine case study is Western Europe. The choice for Western Europe was based on the international context of the chlorine industry and the environmental policy and the transboundary nature of the environmental problems related to chlorine flows.

In Figure 1 the distribution of the chlorine production in Western Europe is illustrated. Germany is by far the largest producer followed by France and the UK. Interesting to see is that two small countries, Belgium and the Netherlands, both have a relatively large chlorine production.

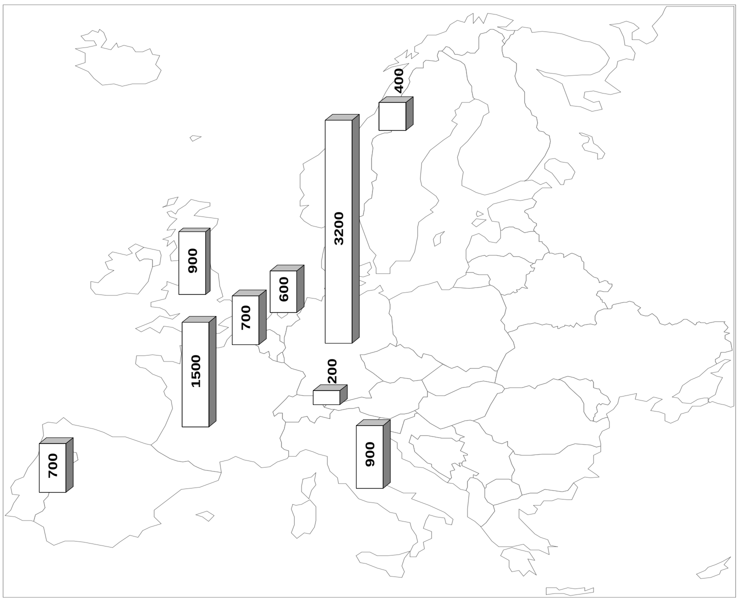

Figure 1: Chlorine production in Western Europe, 1994, kMt (Eurochlor, 1995)

2 Methodology

2.1 Selection of goods and substances

A motivation for choosing the group of chlorinated hydrocarbons as an object of this study is given in Chapter 1. All flows of elementary chlorine, chlorinated hydrocarbons and some important anthropogenic inorganic chlorine compounds are taken into account. A list of main substances in the chemical production processes is given in Figure 3. In Appendix 4a and Appendix 4b the main substances of which emissions are accounted for is given. One of the most important types of stockformation in MFA is the accumulation of substances in durable products. Examples are the use of metals in cutlery, pots and pans, and other 'normal' household products. PVC in the building sector and CFCs in refrigerators and foams were chosen to exemplify the importance of stocks in the anthroposphere on future problemflows..

2.2 Definition of processes

The flows of the chlorine and its compounds are followed from the cradle to the grave: from production to destruction in waste treatment or landfill. Processes are divided in four main groups:

1. **chlorine industry**: chemical production processes in which chlorinated compounds are produced or used as feedstock (e.g. production of PVC from VCM and production of PC from phosgene);
2. **market**: the trade of chlorinated compounds from domestic and foreign producers to domestic and foreign users (e.g. dichloromethane market);
3. **applications**: the use of chlorine and its compounds (e.g. the use of DCM as a solvent in

the pharmaceutical industry or the use of chlorine as a bleaching agent in pulp&paper industry) *excluding* the use as feedstock (e.g. the use of VCM as a feedstock in the PVC production);
4. **waste treatment**: e.g. incineration and landfilling of final waste.

The production processes taken into account in this study are given in Table 2. Markets exist for all chlorinated compounds which are stable enough to transport. In the model a market node is added for all substances which are produced. However, markets are most important for (semi)finished products (e.g. solvents and polymers) and for substances used as feedstock in the chemical industry (e.g. EDC). The main applications can be divided in applications of PVC and applications of chlorinated solvents and CFCs. The main application nodes are given in Table 3. Waste Treatment represents the treatment of final waste and consists of landfill and incineration. Internal waste, which is recycled within the industry and applications, is excluded from this group.

2.3 Definition of system boundaries

The chlorine case focuses on flows in anthroposphere (technosphere, physical economy) and the flows between anthroposphere and environment: extractions and emissions. Flows and formation within the environment are not analyzed in this study although these flows have been found to be significant in some specific cases (de Leer, 1993). However, where it is possible and needed the anthropogenic flows are related to the environmental flows. Flows outside of the chosen region (Western Europe) are not analyzed in this study. However, where possible and needed the relation between flows within Western Europe and flows in the rest of the world is discussed.

2.4 Data sources for the European overview of chlorine flows

National and EuroStat statistics were found to be only of limited use for the chlorine case study in other cases statistical data has proven to be useful for Materials Accounting studies but previous chlorine studies on the national level showed important differences between the statistics and the data provided by the major industries (Tukker et al., 1995). Therefore data was used from earlier studies by others (Ayres & Ayres, 1996) and partly extrapolated to the Western European level from national Dutch data (Tukker et al., 1995). Import and Export data were taken from EuroStat statistics.

During the MAc TEmPo process Ayres & Ayres finished a study that would prove an important basis for the chlorine case (Ayres & Ayres,1996). In their report they quantified the bulk flows of chlorine and its compounds within the Western European chlorine industry. Next to these bulk flows within the industry they presented very limited data on the use and emissions during production and application of these compounds. Ayres & Ayres based their study on a number of data sources, like Tecnon and Euro Chlor, representing the Chlor-Alkali industry. The authors reported important gaps in the data and many inconsistencies when comparing different data sources. Despite all the troubles they had the work of Ayres & Ayres proved to be an important data source for this study. The data of Ayres & Ayres was compared with data of other sources, mainly data provided by EuroChlor.

Data on the applications and emissions of these compounds was largely extrapolated from a national Dutch study of TNO and RUL.CML (Tukker et al., 1995; Kleijn et al., 1997). Tukker et al. quantified around 99% of all the flows of chlorinated hydrocarbons in the Netherlands including applications, waste treatment and emissions during the whole life cycle of chlorine and its compounds.

2.5 Data sources for stock dynamics

For the calculation of stock dynamics of PVC in durable applications data was taken from a study of PVC flows in Sweden (Tukker et al., 1996). In this study all flows of PVC and the main additives, from the cradle to the grave, were quantified for the base year 1994. To calculate the emissions of additives from the PVC-stocks estimates of the magnitude of these stocks were made. These estimated stocks were the bases for further calculations on stock dynamics. For CFCs calculations of stock dynamics were based on world production figures (Worldwatch Institute, 1997) and rough estimations of the distribution of these CFCs over different applications.

2.6 Modelling substance flows

The SFINX (Substance Flow InterNodal exchange) computer program is a tool to assist in substance flow analyses (van der Voet et al., 1995a; van der Voet et al, 1995b). It can be used both as a bookkeeping system and a model. One general rule of mass balances is that the mass inputs of a process equal the mass outputs. This rule is of course derived from the 18th century Lavoisier's *law of conservation of mass*. SFINX is based on Lavoisier's law and can mathematically be described as a static/steady state model based on linear equations.

At present, SFINX users can:

- obtain an overview of all flows and accumulations of a single substance or group of substances within a delineated system;
- check the consistency and completeness of basic data;
- make estimates of any unavailable data through defined relationships within the system;
- present the data and outcome of the calculations in various formats, depending on user requirements;
- calculate the long-term effects of various assumptions such as trends and policy measures;
- identifying the ultimate origins of certain problemflows.

At this moment no dynamic calculations can be performed. The model is therefore not suited for scenario analysis. Stock dynamics is important for future waste treatment and for current and future emissions of substances, which were banned earlier. In paragraph 2.7 Modelling stock dynamics a method is described to include stock dynamics in MFA.

2.7 Modelling stock dynamics

Until recently, MFA has concentrated mostly on flows. During the past few years, MFA researchers have realized that stocks may be equally or more important: *today's stocks are tomorrow's waste flows and emissions.* In the MAc TEmPo project a choice has been made to focus on the stocks in the anthroposphere as well.

The rule of IN = OUT is *the* most basic starting point for MFA. Although the inflows have to equal the outflows in the end (in the *steady state* situation) this might never occur in reality due to chances in regimes and flows over time. If IN > OUT the substance which is studied will accumulate and stocks will be formed within the system. If IN < OUT there will be a negative accumulation and the stocks of the system will be depleted. In MFA practice, where one year is often the base time unit, accumulation will occur if products are consumed with a lifespan longer than one year. It is important to notice that the outflow of the system can be seen as a delayed and reversed (negative) inflow. For our modelling of stocks we have chosen to adopt this approach which has been used before for example for modelling the developement of buildings stocks (e.g. Gabathuler & Wüest, 1984). The stocks are then a result of the combination of inflows and outflows over the years. The time lag equals the lifespan of the products. The lifespan, although generally known as an average, will be distributed in some way: some individual products will be discarded earlier then others. To get an accurate picture of stock formation and depletion the distribution of lifespan should be know. However, empirical data on the lifespan distribution is often not available and the gathering of this empirical data can be very time-consuming. The Swedish group within the MAc TEmPo project has focussed on the gathering and estimation of data on current and past stocks of metals in the city of Stockholm. An alternative for using empirical data would be to assume a certain known lifespan distribution. In terms of Systems Theory: we use a dynamic, linear, deterministic model and assume a known impulse response derived from a discretisized normal distribution[1]. In other words we assume a linear time independent system (LTI). The outflow can thus be calculated as a combination (convolution) of the inflow signal and the lifespan distribution.

In this paper the *output = delayed input* approach described above is used to describe the economy as a system, that responds to an input of products (the *input signal*) with an equal output after a certain delay (the *output signal*). As discussed above time lag is dependent on the lifespan distribution (or disposal function) of the product. The shape of the output signal is determined by the shape of the input signal and by the transformation of this signal by the system.

We used two case studies to apply this approach: PVC in Sweden (0) and CFCs in the (0). The PVC case studies will be published in the near future (Kleijn et al., 1998). A publication of the CFC case study is planned together with the TUW.IWAG.

[1] The choice for a normal distribution is rather arbitrary. A Poisson or Weibull distribution might be more appropriate in some cases. The normal distribution was also choosen as an example of a known impulse response in the book of Baccini & Bader 1996.

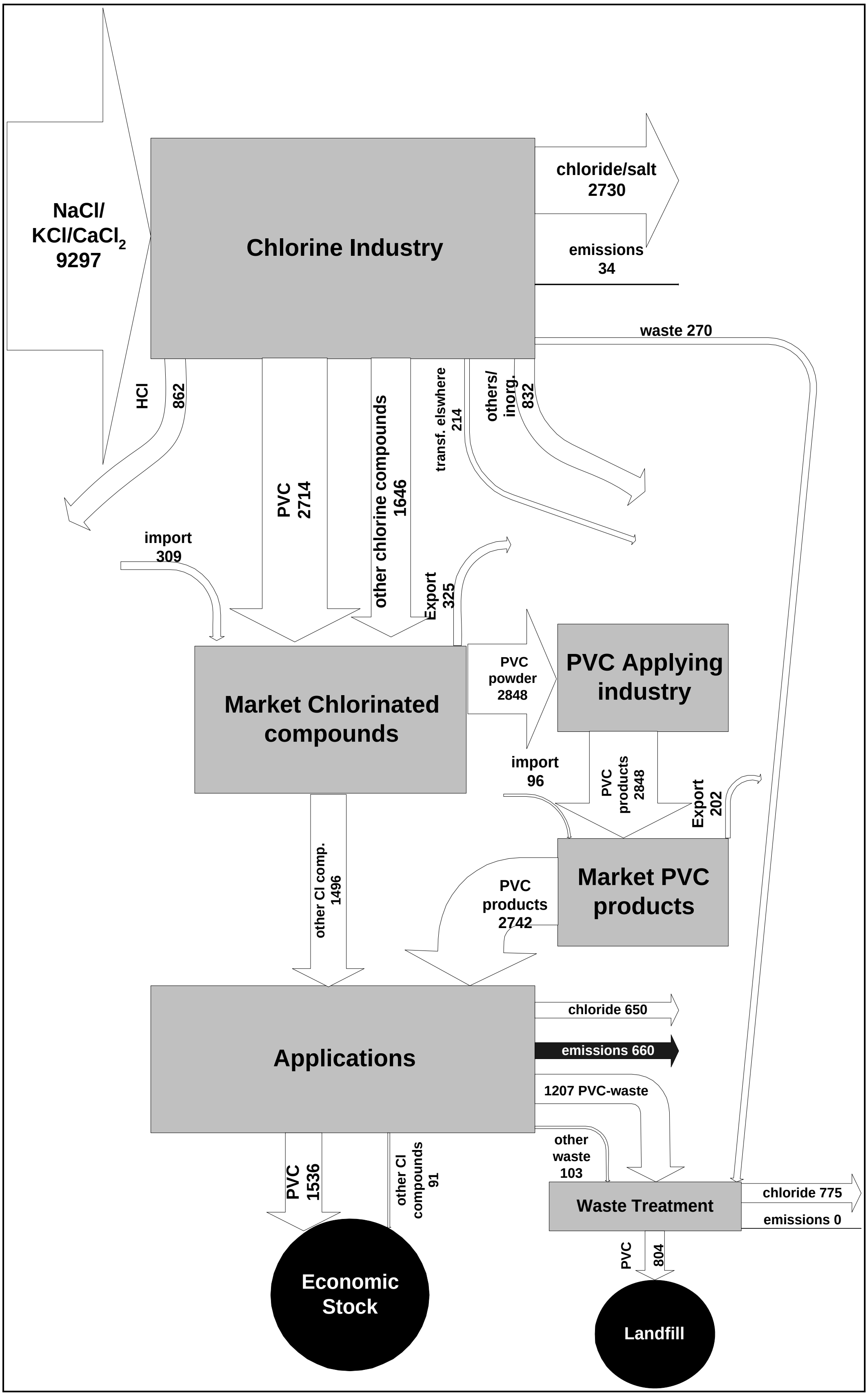

Figure 2: A chlorine balance for Western Europe, 1992 (kMt Cl).

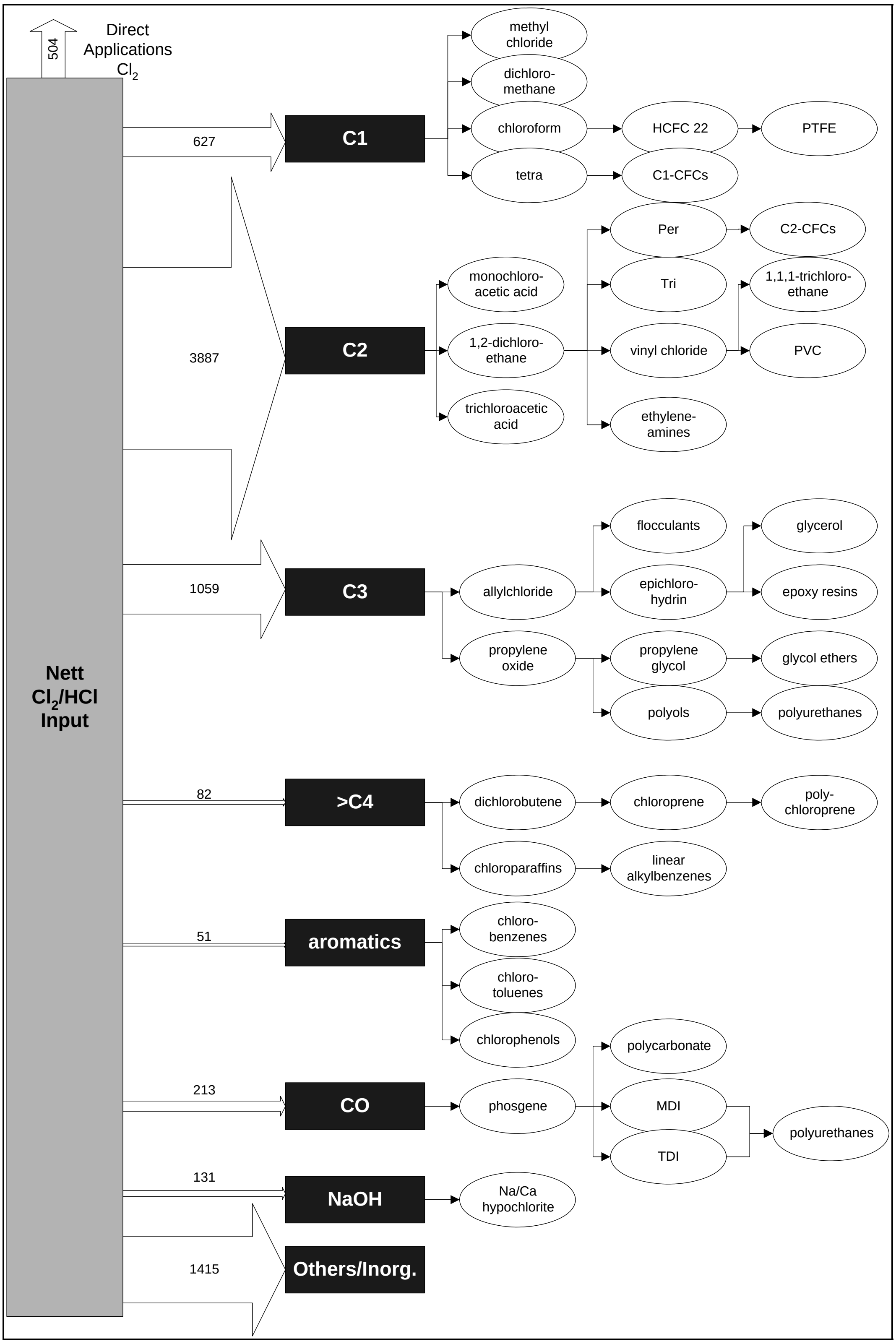

Figure 3: The Backbone of the Western European Chlorine Industry, black rectangles represent non-chlorine part which is combined with HCl or Cl_2 to produce chlorinated compounds. The chlorine input is calculated by adding the Cl_2 input and the HCl input and subtracting the HCl formation (quantities based on Ayres & Ayres 1996).

3 Main results obtained

3.1 A chlorine balance for Western Europe

In Figure 2 the flows of chlorine and its compounds through Western Europe is summarized. By far the most important chlorine feedstock is ordinary table salt (NaCl) from mineral deposits. Around 30% of the chloride which flows into the industry in salts is emitted to the environment as chloride salts, mostly after temporary having been incorporated in chlorinated hydrocarbons. Somewhat less than 55% is incorporated in chlorinated hydrocarbons as products other than HCl. PVC is by far the most important single product of the chlorine industry. Another 10% are used in other industries as HCl and some 5% are used directly as elementary chlorine in the pulp&paper industry and in water treatment.

3.2 The backbone of the chlorine flows in Western Europe

In Figure 3 the backbone of the chlorine industry in Western Europe is given. Next to the direct applications of chlorine there are 7 important vertebrae in the backbone, which represent the non-chlorine part which is combined with chlorine or HCl to produce chlorinated compounds. More than half of the net inflow is used in the C2 (ethane, ethene) vertebra. About 14% are used in the C3 (propane, propene) vertebra and about 8% in the C1 (methane). Around 3% are used for a reaction with CO to form phosgene and around 2% to react with caustic (NaOH) to form hypochlorite. Minor amounts are used as input for C4 (butane, butene) and aromatics. Another 19% are used in the production of other compounds, mainly inorganics

3.2.1 Production and use of elementary chlorine (Cl2)

Chlorine is produced by the electrolysis of brine: a solution of common salt, NaCl. Eurochlor reported a production of 8610 kMt (Ayres & Ayres, 1996). About 93% of the chloride that flows in as chloride salts and HCl is converted to chlorine of which 94% is used in chemical production processes while the remaining 6% is used directly as bleaching agent in the pulp&paper industry and water treatment. The remaining 7% is emitted, mainly as chloride salts.

In Figure 4 the use of chlorine is given. More than 94% of the produced Chlorine is used as basic material in the chemical industry to produce other compounds. The remaining 6 % percent of the chlorine are used in direct applications. An explanation of the abbreviations used in the figure is given in Table 2.

3.2.2 Production and use of the second chlorine feedstock in the chemical industry: HCl

Next to elementary chlorine there is another important chlorine feedstock that is not so well known outside the chemical industry: hydrochloric acid (HCl). However, primary production of HCl does not occur except for a very small amount of very pure HCl which is needed in some specific processes. This pure HCl is produced by mixing chlorine gas (Cl_2) with hydrogen gas (H_2), both produced in the production of chlorine. The rest of the HCl is produced as a byproduct of a number of important processes in the chlorine industry. There are two important sources: the production of chlorine-free products with chlorinated starting materials and the incineration of chlorinated waste. In a sense one could view the use of HCl as a chlorine feedstock as *recycling* of chlorine. The production of PVC is by far the biggest use of the HCl produced as a waste product of other production processes. Thus PVC is not only the biggest single product of the chlorine industry, it also permits the production of other products because it processes the wastes produced during their production processes. It is important to note this link between PVC and the rest of the chlorine industry when discussing policy measures focussed on (partly) banning PVC. In Figure 5 the production and consumption of HCl is given.

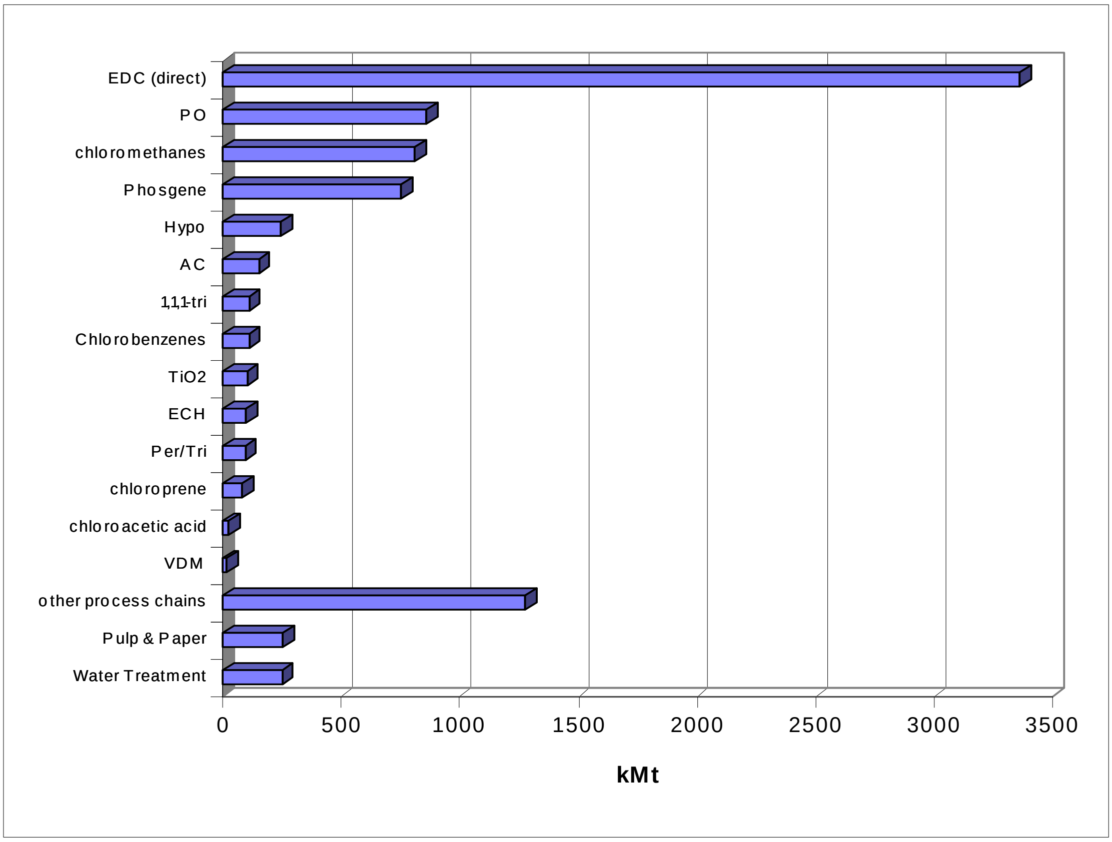

Figure 4: The use of Chlorine in Western Europe in 1992 (based on Ayres & Ayres, 1996)

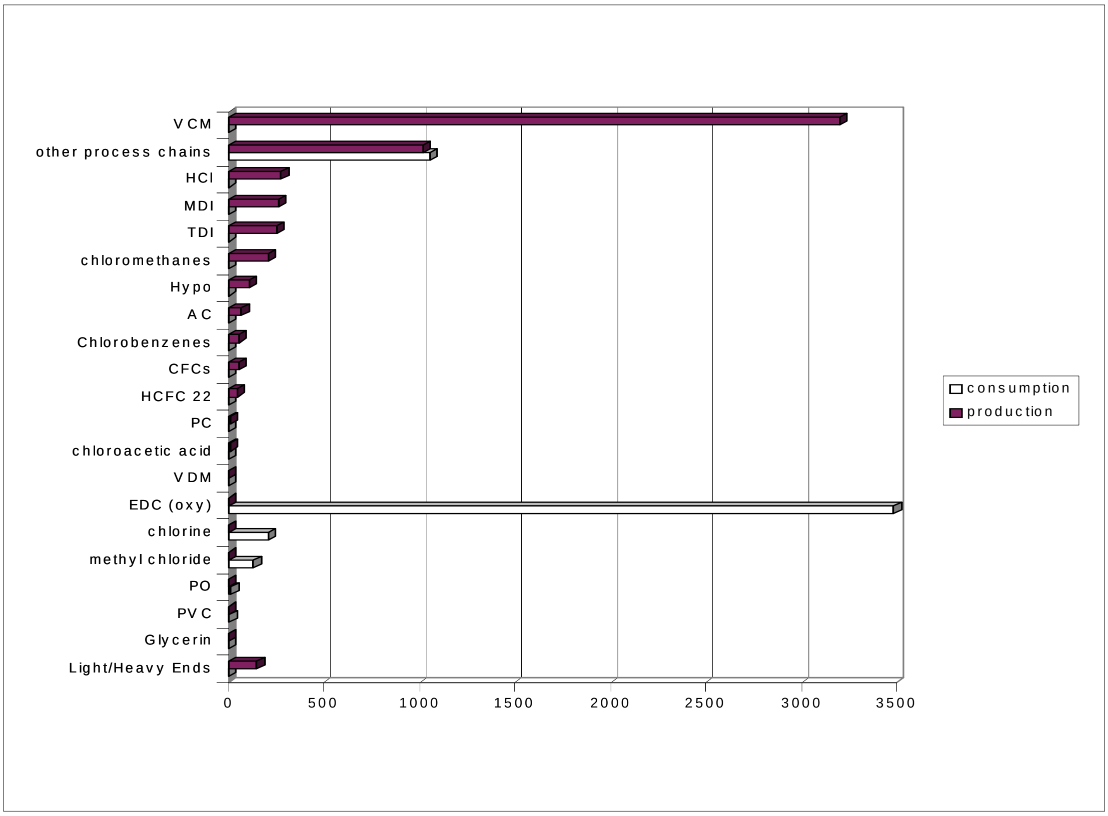

Figure 5: Production and Consumption of HCl in the Chlorine Industry in Western Europe in 1992 in kMt chlorine (based on Ayres & Ayres, 1996).

3.2.3 Chlorinated C1-derivates from the cradle to the grave

Chlorine flows into the C1-derivates production in the form of Cl_2, HCl and Light and Heavy ends (waste products of chlorination processes). There is a net production of HCl and a net consumption of Light and Heavy -ends in this vertebra. Less than half of the chlorine input flows to the market in chlorinated products where net export occurs. This leaves 413 kMt chlorine in C1-derivates to be used in applications. The largest part of products consists of solvents (DCM, chloroform and tetra) and (H)CFCs. Around three quarters of the inflow will be emitted to air. The rest is partly accumulated in stocks in the anthroposphere ((H)CFCs) and partly treated as chemical waste (solvents).

3.2.4 Chlorinated C2-derivates from the cradle to the grave

In terms of chlorine throughput the C2-derivates vertebra is by far the most important. Large amounts of chlorine flow into this sector in Cl_2 and HCl. There is a net consumption of HCl and a net production of Light and Heavy ends in this vertebra. Less than halve of the total chlorine inflow goes to the market as chlorinated products where a small net export occurs. The most important single product is of course PVC. The other products are chlorinated solvents: 1,1,1-tri, Per and Tri. These solvents are used in applications where more than 80% is emitted to air (excluding internal recycling). The rest ends up the chemical waste and emissions to water.

PVC is used in several applications. In general the PVC can be divided into two types: rigid and flexible PVC. Rigid PVC is mostly used as a construction material and in packaging. Flexible PVC is produced by adding large amounts (up to 50%) of plastisisers and can be used in flooring, coatings etc. In Western Europe in 1992 37% of the PVC was used as flexible PVC and 63% as rigid PVC. Most important rigid applications are pipes&fittings, profiles, films&sheet and bottles. Most important flexible applications are cables, film&sheet, flooring, wall covering and hosepipe.

PVC used in construction applications, especially pipes, will remain in the anthroposphere for as long the lifespan of the constructions (50-100 years). Applications such as wallpaper and flooring have much shorter lifespan (less than 10 years). PVC used in packaging has a lifespan of less than 1 year. The PVC which is used in construction at this moment will be turned into waste after a number of decades. At this moment only minor amounts of PVC are found in building waste because the use of PVC in construction has started only a few decades ago and has risen sharply since then. Therefore an important part of the PVC that goes to applications at this moment will accumulate in the stock in the anthroposphere. From the PVC going into waste treatment, around two third will be landfilled. One third will be incinerated (EEA, 1995), most of the chlorine ending up as chloride.

3.2.5 Other chlorinated compounds from the cradle to the grave

Most of the chlorine flowing into the C3 branch is transformed to chloride during the production of propylene oxide, ECH, epoxy resins and glycerin. Almost halve of the total chlorine inflow goes to the market as chloroprene rubber where a small net import occurs. The lifespan of chloroprene is unknown. It is assumed that most of the chloroprene will accumulate in the anthroposphere. Chlorobenzenes are used in the production of pesticides, pharmaceutics, dyes etc. partly as feedstock and partly as solvent and are assumed to be transformed elsewhere. Most of the produced phosgene is transformed to HCl during the production of TDI and MDI (intermediates for the production of polyurethane foams) and to chloride salt in the production of MDI and polycarbonate (PC). Less than half of the amount of chlorine used to produce hypochlorite goes to the market as hypochlorite. The other half is transformed to HCl during the production. Hypochlorite is used as a disinfectant in households, swimming pools, the preparation of drinking water, industrial-cooling systems. During the use of hypochlorite it is largely transformed to chloride. Because hypochlorite is an active form of chlorine it will react with organic material and partly chlorinate this material. Formation of volatile chlorinated hydrocarbons is known to occur in swimming pools.

3.3 Modelling of PVC stocks in Sweden

As described in paragraph 2.7 Modelling stock dynamics the outflow (output signal) of a material in a certain year depends on both the inflows in the years before and the lifespan distribution. In this paragraph we describe the main results of a test in which we used PVC in Sweden as an example. In this test, stock modelling was used to estimate future waste flows on the basis of a minimum amount of data. The one figure known for Swedish situation was an estimated stock in different products in 1994 (Tukker et al., 1996). This stock 1994 can be a result of different types of stock building. Five different examples are discussed in this paragraph:

- the simplest assumption would be a constant inflow since the introduction of the different products together with an exact known lifespan of these products;
- another possible inflow curve would be the result of linear increasing inflow, again combined with an exact known lifetime;
- a third possibility would be an exponential increase since the introduction of the products combined with an exact known lifespan;

To show the influence of adding a normal distribution to the lifespan a fourth and fifth model were generated:

- a combination of the first model (constant inflow) with a discretisized normal distribution used for the lifespan
- a combination of the second model (linear increase) with a dicretisized normal distribution used for the lifespan

In Figure 6 the results of the five models are shown. All outflows are a combination of the outflow of the three main products: pipes, flooring and cables. Just for the sake of this example it was assumed that the use of each of these products would linearly decrease to zero from 1995 to 2010 as a result of some phasing out policy. Because the use of every product started at a different point in time and because the lifespan is different for each product the form of the outflow curves is much more complex than one would expect on the basis of the outflow curve of every single product. From Figure 6 it can be concluded that predicted waste flows are quite similar for a constant inflow and a linearly increasing inflow. This is even more true when the curves are smoothened by adding a discretisized normal distribution for the lifespan. The exponential curve, however, gives peaks, which are very much higher than the other models. A preliminary conclusion from this exercise could be that it is important to know whether the inflow has been increasing more than linearly in the past e.g. in the case of products belonging to a fashion like certain types of PVC clothing. This may be more important than having exact time series data on past inflows.

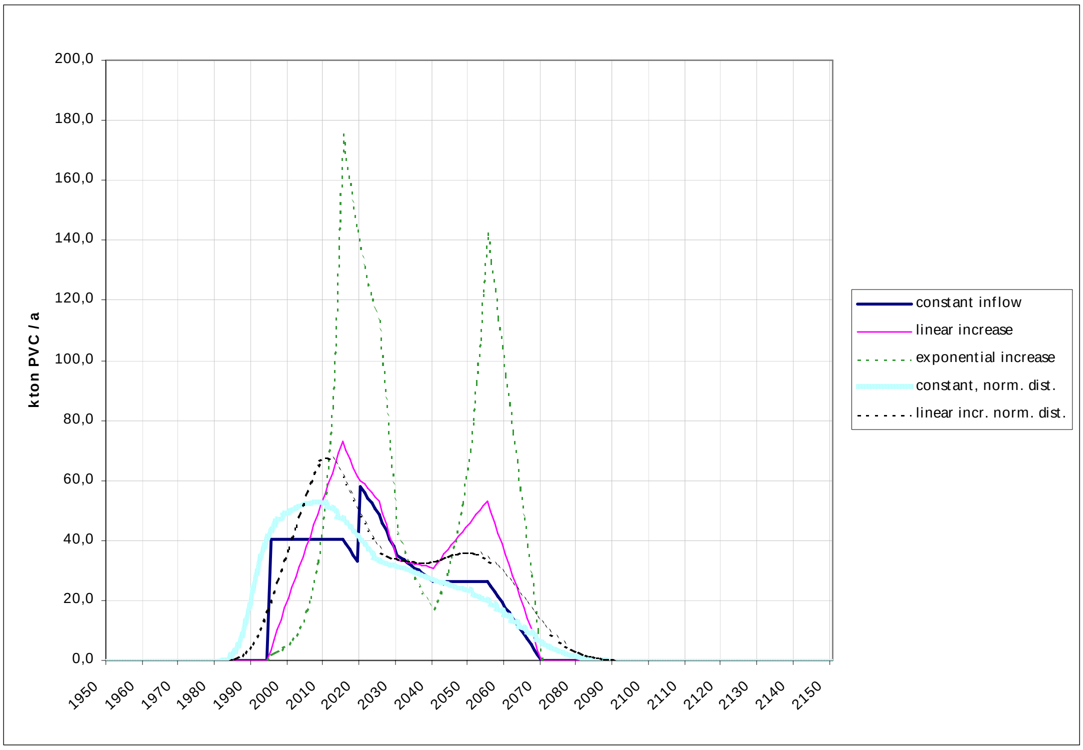

Figure 6: PVC waste flows (outflow) from pipes, cables and flooring in Sweden calculated with different models for the consumption (inflow) and different lifespan distributions

3.4 Stock modelling for CFCs in the world

CFCs have been used in a large number of applications. The best-known applications to the public are the use as propellant in spray cans and the use in refrigerators. However CFCs have also been used in the industry as solvent and cleaning agents and as a blowing agent in different types of foams. Important applications of these foams are as isolating material in the building sector and in refrigerators. In fact most of the CFCs in refrigerators are incorporated in the isolating foams. CFCs are thus only partly used in applications which immediately lead to emissions (propellants and solvents) in the other types of use there will be delayed emission. Emissions from the latter applications can be expected during the use of the products and during waste processing. Just as in the case of PVC the outflow curve (in this example emission) is dependent on the inflow curves and the lifespan distribution of the products. For CFCs in foam the situation is a little more complex because there is a diffuse emission when the foams are in use, an emission of CFCs when the products (mostly buildings) in which the foams are used are being demolished and, if the waste is landfilled, there will be a diffuse emission from the waste at these landfill sites. Thus the residence time of CFCs in the foam is not equal to the lifespan of the products.

In this example we used time series data of the production of CFCs in the world from 1950 to 1995 (Worldwatch Institute, 1996). In this database the amount used as propellant was specified. The distribution over the other applications was based on extrapolation of Dutch data. Average lifespans of the different products were estimated and a normal distribution was applied to this average lifespan.

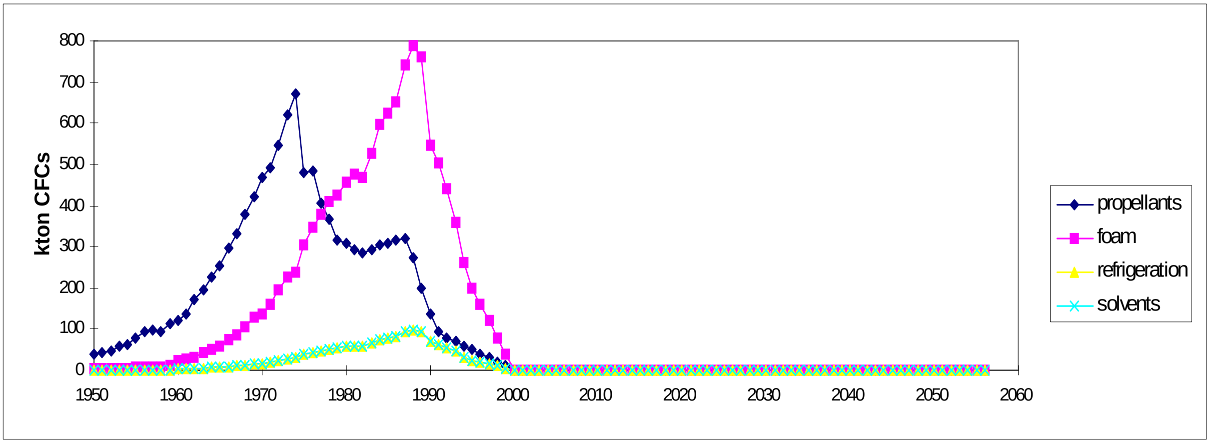

Figure 7: World use of CFCs in different applications (propellants plus total data, Worldwatch Institute, 1996; distribution over other applications calculated on the basis of Dutch data)

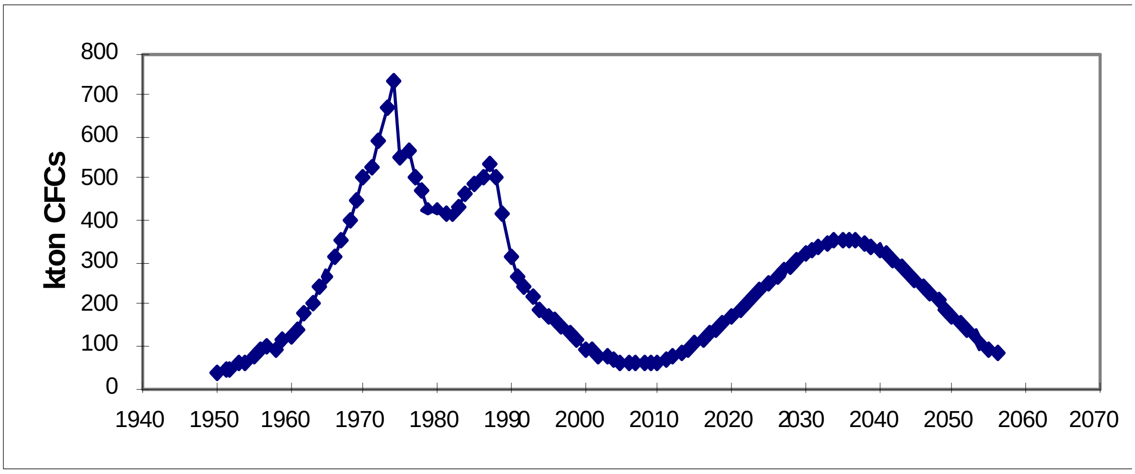

Figure 8: Calculated world emissions of CFCs

Figure 7 shows the results of the combination of the world production data, the data on use of propellants and the Dutch distribution over the other applications. Figure 8 shows the calculated total emissions of CFCs. It was assumed that the CFCs used in solvents and propellants were emitted in the same year as they were produced. The average lifespan for CFCs in refrigeration was estimated to be 10 (sd 2 years) years. In building foams it was estimated to be 50 years (sd 10 years) (a combination of lifespan of buildings and the diffuse emissions during use). The emission curve shows three peaks: one at the peak of the use of CFCs as propellants (1974), one as a combination of the starting use of CFCs in building foams and a reviving propellant use (1987) and one as a result of a delayed outflow from foams used in the building industry (2036). This means that even after a complete phase-out we may expect a CFC emission peak, dying out only after 2050 unless additional measures are taken to avoid the emission of CFCs from insulation foam during the demolition of buildings. Although these calculations are based on a number of very rough assumptions it indicates that further research into this topic is needed. In a combined effort RUL.CML and TUW.IWAG will write a paper on this subject.

3.5 Incorporation of chlorinated micropollutants in a chlorine MFA

In the discussions around the use of chlorine and chlorinated compounds chlorinated micro-pollutants are one of the key points. When one looks at toxic compounds that pose problems at a global scale one will find that many of these compounds are chlorinated. Well-known examples are PCBs, dioxins, DDT, drins, toxaphene and chlorodane. It is important to make a distinction between three groups of compounds:

1. pesticides, which are emitted on purpose with a certain functionality
2. compounds like PCBs which have a functional use but are not emitted on purpose
3. compounds like dioxins which are emitted as byproducts of certain processes

In the last two decades the production and use of the first two types compounds have been regulated quite strictly. Most of the *old generation* organochlorine pesticides such as DDT, drins and lindane have been banned in the western world, although some of them are still used in developing countries. The production of PCBs has also been banned although there is still a large amount in use in closed applications. The emissions of dioxins have been reduced drastically in the western world due to the banning of uncontrolled burning of waste products and the installation of flue-gas treatment facilities in waste incineration plants. However, it is important to notice that although all these measures mentioned above are in active there these compounds are still found in organisms in very high concentrations (especially in arctic areas). An important question which remains is whether we are still unknowingly emitting other persistent compounds with bioaccumulating and toxic potential. In other words *are we emitting the dioxins of the future right at this moment ?*

In some publications the property of chlorine to change easily from one molecule to another (the reactivity of chlorine and its compounds) is believed to be a reason to ban chlorine as a starting material for the chlorine industry (Muir et al., 1993). The environmental movement subscribes this opinion. The chlorine industry, however, states that actions should be aimed only at those processes and products which pose a proven risk to humans or ecosystems.

One of the main knowledge gaps we found in an MFA for chlorinated substances in the Netherlands was the possible emissions of chlorinated micropollutants (Tukker et al., 1995). Well known substances like dioxins are well monitored and emissions of these compounds are therefore well known. However, not all of the AOX in effluents of processes in which chlorine is used can be explained by the emissions of known components. Thus an emission remains of unknown compounds with unknown effects. This uncertainty can be dealt with in different ways. One might start an comprehensive monitoring program focussed on identifying individual compounds in these effluents coupled to research to determine the persistency, bioaccumulative potential and toxicity of these compounds. A different approach would be to skip the step of identification and start testing the whole effluent for persistency, bioaccumulative potential and toxicity (the *total effluent* approach). Both approaches need a considerable amount of research. It is clear that identifying the thousands of different compounds in the AOX mixture is not so easy. Therefore the total effluent measurements might seem a good alternative. The problem with this latter approach is that it requires a completely new set of measurements that have to be developed via fundamental research before it can be put to practical use.

The question still remains how such a complex subject on which so little data is available can be dealt with in MFA. One way of tackling this problem would be to make a sensitivity analysis in which the toxicity of the certain known chlorinated micro-pollutants (e.g. 2,3,7,8-TCDD) are used to express toxicity for the unknown emissions. In this way worst, average and best case scenarios can be made.

4 Consequences for implementation

4.1 Policy implications of the study of European chlorine flows

In this study an overview was created of flows of chlorinated compounds in Western Europe from *the cradle to the grave*. The production of PVC is by far the most important single product in the chlorine chain. Next to that an important amount is used for the production of products which do not contain chlorine themselves like propylene oxide, polyurethanes and polycarbonate. Another important type of products are chlorinated solvents, although the use of these solvents is more and more restricted. Based on figures for the Dutch situation the biggest emissions come from the applications of chlorinated products, especially solvents. Emissions from production sites have been reduced drastically the last decades. Although the emissions from the production sites are small in terms of mass, they can still be important from an environmental point of view. There is still the possibility that unknown bioaccumulating, persistent and toxic chlorinated micropollutants are emitted. Although MFA is better suited for quantifying bulkflows, methods should be developed to incorporate these small flows, such as indicated above. Policy makers should be aware of the large amount of interconnections between the different processes and products within the chlorine industry. One of the most important connections is that between the production of HCl as a byproduct in many processes in the chlorine industry, including the incineration of chemical waste, and the use of this HCl in the production of PVC. A ban on PVC would cause a large surplus of HCl which would become a waste product. Thereby a ban on PVC could also be the end of many other products from the chlorine industry.

The results of the examples of stock modeling for CFCs and PVC have some important policy implications. First of all it is clear that stock formation can reduce the effect of source oriented policy measures to large extent: although very strict regulations are in place to reduce the production and use of CFCs, the emissions from stocks in the anthroposphere will remain for another two decades. In the case of PVC there is much discussion going on at this moment about the possibilities to recycle PVC. However, the amount of recycling is only marginal compared to the amount of PVC still in stocks in the anthroposphere. Because recycling is only marginal at this moment it is hard to assess whether the much bigger waste flows of the future can really be handled via recycling. If we would find out in the next couple of years that PVC-recycling is not an environmental sound option for PVC waste treatment we policy measures focussed on reducing the PVC input will have effects only after 10-50 years. Another important example of how stock building can reduce the effects of policy measures is the use of PCBs. Although the production of PCBs was banned decades ago there is still a large amount of PCBs in use at this moment (mostly as cooling/insulation liquids in transformers). Policy makers should be made aware of the fact that stock formation can be an indicator for future problems.

The question whether or not a ban on the use of chlorine in the chemical industry would be a good thing for the environment can not be answered on the basis of this study. There are still some important problems left within the chlorine industry and during the applications its products which should be examined further. Especially the subject of chlorinated micropollutants should be investigated. However, it is not clear that a substitution of the chlorine industry with other chemical production processes would cause less environmental problems. This study can be used to focuss the attention on the dirty spots in the chlorine chain.

4.2 MFA as a policy supporting instrument

The use of MFA as a policy supporting instrument can not be shown on the basis of the MAc TEmPo case study since it has not been used yet in a policy context. However, it can be shown on the basis of previous case studies.

<u>The Dutch Chlorine Balance (Tukker et al., 1995)</u>
This study, carried out by the Netherlands Organization for Applied Scientific Research (TNO) and the Centre of Environmental Science Leiden (RUL.CML), was commissioned by the Dutch Ministries of Housing, Physical Planning and Environment, Economic Affairs, and Traffic, Public Works and Waterways (Tukker et al., 1995). The study lasted for a period of two years, starting in September 1993.

The first phase of the study was set up as an MFA, covering about 99 % of the flows of chlorinated substances in the Netherlands. Emissions, waste generation, exports, imports, and economical transactions have been collected making use of all sources possible: the Dutch emission registration database, LCA-databases, industrial data etc. Emissions were evaluated making use of the characterization step from the LCA (Life Cycle Assessment) methodology. Emissions with toxicological effects have been additionally evaluated on the basis of actual risk assessments of the National Institute of Public Health and Environmental Protection (RIVM). This resulted in about 6 groups of priority segments of the Dutch chlorine chain, for which additional measures are being prepared. The study showed that the structural danger connected to the chlorine chain as pronounced by the environmental groups are not supported by the present knowledge about emissions and impact assessment. However the study also indicates that important uncertainties exist that require attention, especially concerning the possible emissions of persistent bioaccumulating toxic micropollutants. At this moment RUL.CML is involved in the BITAC: an advisory commission of the Dutch Ministry of Housing, Physical Planning and Environment. The task of the BITAC is to follow and coordinate the policy actions focussed on the problemflows found in the Chlorine Balance study. Other members of the BITAC are representatives from industry, environmental movement, labor union and the Ministry of Traffic, Public Works and Waterways.

In the Dutch Chlorine Balance study MFA proved to be a very useful policy-supporting tool. A quantitative overview of 99% of the flows of chlorinated substances can serve as a factual starting point for further discussions on chlorine policy. Because the overview was relatively complete, problem flows could be identified and compared with each other on the basis of potential contributions to environmental problems. With the MFA links within the chlorine between different flows and processes chain have been made visible. Furthermore, gaps in the current knowledge were found which were used to focus future research efforts.

<u>Flows of six heavy metals in the economy and environment of The Netherlands (Annema et al., 1996)</u>
Heavy metals are since long a concern of environmental policy. In The Netherlands, standards have been set, measures have been taken and policies have been formulated for various aspects of the heavy metals problem. This study has been undertaken to provide the Dutch government with an integrative framework, wherein the various policies can be placed and the need for further measures can be identified. For six heavy metals - copper, zinc, lead, chromium, cadmium and mercury - the flows through the economy and the environment were quantified, thus providing an overview of the metals' chain from cradle to grave. These overviews have been translated into substance flow models with help of the computer tool SFINX, which have been used to calculate the origins of several specific environmental problems and calculate the effectiveness of certain possible abatement measures. It appeared that, although some problems occurred for one metal only, there were several problems concerning the group of metals as a whole due to their non-degradability. One problem is the metals accumulation in agricultural flows such as soils and manure, as a result of constant recycling. Another is the content in waste products such as sewage sludge, compost and fly ash, which makes re-use of these materials impossible. This study was one of studies on which the Dutch government has based current policies for heavy metals.

Benefits of MFA as a decision support tools
One of the most important functions of MFA is to couple environmental problem flows to anthropogene origins. In the study of heavy metals in the Netherlands SFINX static modeling was used to calculate the effectiveness of current heavy metal policy and certain alternative policy measures. In the Dutch Chlorine Balance study environmental problemflows were coupled to processes in the anthroposphere. The risks of emissions were calculated with the aid of equivalency factors expressing the potential contribution of different substances to different environmental problems. This resulted in a priority list of emissions. Furthermore, the MFA helped to focus attention of policymakers on gaps in the current knowledge.

When stock formation is included in MFA, it can be used as a tool for early recognition of future waste and emission problems. The stock modeling can used to estimate future outflows on the basis of quantitative and qualitative information of past inflows and lifespan of different products.

Opportunities and threats

A big underdeveloped opportunity for the use of MFA as a policy-supporting instrument is the use of MFA-indicators as satellite indicators next to economic indicators in environmental reports of nations, local governments and companies. A major threat for the use of MFA is the fact that gathering data for MFA is very time consuming. If statistical data and emission inventories would be better accessible and confidentially problems would be tackled an important part of this problem would be solved.

5 Discussion & Conclusions

In this MAc TEmPo case study an overview of flows of chlorinated compounds within the Western Europe is given together with the emissions of these compounds to the environment (more detailed information can be found in the case study report: Kleijn & van der Voet 1998). A number of problemflows connected to methodological problems were identified and studied in more detail: emissions and waste from stocks of PVC and CFCs and emissions of chlorinated micropollutants.

From the study of stocks of PVC in Sweden it is clear that even if we stop using PVC within the next 10 years the PVC waste flows will remain until the edge of the 22^{nd} -century. From a methodological point of view it is shown that very simple models can be used to show the importance of certain problemflows.

From the study of stocks of CFCs in the world it can be concluded that the emissions of CFCs will remain until around 2060, even if the use in developing countries would decrease just as the use in the developed countries (which seems very unlikely at this moment). It should be noted that the results for CFCs are based on first assumptions on the distribution of CFCs over different applications and on the lifetime of CFCs in different goods. Further investigation in this subject is planned together with the TUW.IWAG.

From the study of chlorinated compounds in the Netherlands it is clear that the emissions of chlorinated micro-pollutants are an important gap in the current knowledge. A number of routes to close this gap are discussed and will be further discussed within the framework of the BITAC: the steering committee assembled by the Dutch Ministry of Environment to follow the policy actions which resulted from the Dutch Chlorine chain study.

In both the Dutch Chlorine Chain study (Tukker et al, 1995; Kleijn et al., 1997), the Swedish PVC study (Tukker et al., 1996; Tukker et al., 1997) and in the MAc TEmPo case study of flows of chlorinated compounds in the Western Europe it was found that MFA can be a powerful decision supporting tool to focus a complex discussion on important problemflows. However, in every policy decision certain uncertainties will remain. MFA can be an important aid to help reduce these uncertainties by providing structured data but in the end policy makers will have to find a way to cope with remaining uncertainties. However, one might

argue that making decisions in situations where there is a certain amount of uncertainty left is typically the job of policy makers and that the job of the scientists would be to minimize these uncertainties.

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Table 1 List of used abbreviations

1,1,1-tri	1,1,1-trichloroethane
1,2-DCE	1,2-dichloroethane
AC	allyl chloride
C1	the group of hydrocarbons with 1 carbon atom (methane derivates)
C2	the group of hydrocarbons with 2 carbon atoms (ethane derivates)
C3	the group of hydrocarbons with 3 carbon atoms (propane derivates)
C4	the group of hydrocarbons with 4 carbon atoms (butane derivates)
>C4	the group of lydrocarbons with more than 4 C atoms (non cyclic)
CaCl2	calcium chloride
CFCs	chlorofluorocarbons
Cl2	elementary chlorine
RUL.CML	Centre of Environmental Science, Leiden University
CO	carbon monoxide
DCM	dichloromethane
EC	European Union
ECH	epichlorohydrin
EDC	1,2-dichloroethane
EDC(oxy)	oxychlorination production process for 1,2-dichloroethane
EDC(direct)	direct chlorination production process for 1,2-dichloroethane
EU	European Union
GNP	gross national product
HCFCs	hydrogen chlorofluorocarbons
HCl	hydrogen chloride, hydrochloric acid
hypo	hypochlorite
KCl	potassium chloride
kMt	kilo metric tonne
L/H ends	Light and Heavy ends, chemical waste recycled in the chemical industry
MCPA	4-chlorine-2-methyl-phenoxyhydrochloric acid
MCPP	4-chlorine-2-methyl-phenoxypropionic acid
MDI	4,4’-diphenylmethane diisocyanate
NaCl	sodium chloride, common salt
NaOH	caustic soda
PC	polycarbonate
PCBs	polychlorinated biphenyls
Per	perchloroethylene
PO	propylene oxide
PTFE	polytetrafluoroethene
PUR	polyurethanes
PVC	polyvinylchloride
MFA	material flow analysis
SFINX	substance flow internodal exchange (computer model)
TDI	toluene diisocyanate
TiO2	titanium dioxide
TNO	Netherlands Organization for Applied Scientific research
Tri	trichloroethylene
VCM	vinylchloride (monomer)
VDM	vinylidene chloride
WE	Western Europe

Table 2: Production Processes in the Western European Chlorine Industry

Name	Description
chlorine	electrolysis of brine to produce Cl_2
HCl	direct production of HCl from salt (thus not as a byproduct of other chlorinated compounds)
chloromethanes	direct chlorination of methane with Cl_2 to produce dichloromethane, chloroform and tetra
CFCs	production of C1-chlorinated fluorocarbons from tetrachloromethane and HF
HCFC 22	production of HCFC 22 from chloroform and HF
methyl chloride	production of methyl chloride from HCl and methane
EDC (direct)	direct chlorination of ethene with Cl_2 to produce 1,2-dichloroethane
EDC (oxy)	oxychlorination of ethene with HCl to produce 1,2-dichloroethane
VCM	cracking of 1,2-dichloroethane to produce monochlororethene (vinyl chloride, VCM)
PVC	polymerization of VCM to produce polyvinylchloride
VDM	production of vinylidene chloride via 1,1,2-trichloroethane and 1,2-dichloroethane
ethylene amines	production of chlorine-free ethylene amines from 1,2-dichloroethane, NH_3 and NaOH
Per/Tri	production of tetrachloroethene (Per) and trichloroethene (Tri), partly from 1,2-DCE and Cl_2
1,1,1-tri	production 1,1,1-trichloroethane from vinyl chloride and Cl_2
chloroacetic acid	production of chloroacetic acid from acetic acid and Cl_2
AC	production of 3-chloropropene (allyl chloride, AC) from propene and Cl_2
ECH	production of epichlorohydrin (ECH) via dichlorohydrin from allyl chloride and hypochlorite and $Ca(OH)_2$
PO	production of Propylene Oxide via propylene chlorohydrin from propene and Cl_2
epoxy	production of epoxy resins from epichlorohydrin
glycerin	production of glycerin from epichlorohydrin
chloroprene	production of 2-chloro-1,3-butadiene (chloroprene) from 1,3-butadiene and Cl_2
phosgene	production of $COCl_2$ (phosgene) from carbon monoxide and Cl_2
chlorobenzenes	production of chlorobenzenes from benzene and Cl_2
PC	production of polycarbonate from phosgene and Bisphenol-A
TDI	production of toluene diisocyanate (TDI) from phosgene and toluene diamine
MDI	production of 4,4'-diphenylmethane diisocyanate (MDI) from phosgene and diaminodiphenylmethane (MDA)
hypo	production of hypochlorite from Cl_2 and NaOH
TiO_2	production of titanium dioxide (TiO_2)
other process chains	production of other compounds, mainly inorganic

Table 3: Applications of chlorinated substances in the Western Europe

Name	Description
Solvents/CFCs	
metals/electronics	degreasing agents in the metal and electronic industry
dry cleaning	solvent used for cleaning clothes
graphical industry	solvent in the printing ink
pharmaceutical industry	solvent in production of pharmaceutical products
foodstuffs (extraction)	solvent used to extract compounds from feedstuffs e.g. caffeine from coffee
paint remover	solvent used to remove paint or adhesives from painted surfaces
adhesives	solvent used in adhesive products
aerosols	solvents used as propellants in aerosols
paint	solvent used in paints
textile refinement	textile refinement
yarns/fibres	solvents used in the production of yarns and fibres
household/industrial cooling	(H)CFCs used in cooling equipement
foam	solvents used as blowing agent to create foams
sterilisation gas	CFC-12 used as sterilisation gas
(chemical) industry	other use in the chemical industry
PVC	
pipes&fittings	pipes&fittings used for distributing e.g. water and gas and collection of sewer
profiles	profiles used mainly in building applications e.g. windowframes
film&sheet	film & sheet used for coatings, glazing etc.
bottles	PVC-bottles
cables	insulating material for electricity cables
flooring	PVC-flooring, vinyl flooring
wall covering	PVC-wall covering, vinyl wall covering
hosepipe	PVC hosepipes, flexible pipes&hoses
other	other applications of PVC

ANNEX 4 to SUMMARY REPORT
Report of the contractor TUW.IO

Identification of Material Flow Systems

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1 Introduction

The main aim of the EOS[1] group within MAc TEmPo is to provide methods for data based modelling in MFA. In addition our work shall enhance the understanding of the structure of an MFA system (system analysis) and provide tools for scenario simulation. In general, the object was to demonstrate that system theory (in particular system identification) can contribute considerably to make MFA more efficient (see also Bauer et al., 1997, and Gleiß et al., 1998).

Starting at the flow sheet and the available data, the following questions arise:

- Data reconciliation
- Estimation of unmeasured flows
- Estimation of transfer coefficients
- Analysis of the system structure
- Scenario simulation

These problems have been solved to a satisfactory degree of completeness for the linear, static case.

Based on the investigation of different types of stock dynamics in co-operation with the MAc TEmPo partners, the development of a dynamic material flow model using the concepts and methods of system theory has been started. The most important parts of system theory in this context are structure theory of linear, dynamic systems, Errors-in-Variables modelling and the theory of non-negative systems. Due to the special structure of MFA problems, special models and methods have to be developed.

Up to now, three types of stock dynamics have been investigated. A general model for dynamic material flow systems has been set up. The investigation of system theoretic (e.g. stability, controllability) and estimation aspects of special model classes for each of the three stock types has been started.

2 Static modelling

In this section we consider static, linear, stochastic models for material flows are considered. We are concerned with

1. Data reconciliation, estimation of unmeasured flows and of the model parameters (transfer coefficients); showing the „white spots“ in the system, where additional measurements are necessary in order to obtain unique results

[1] Institute for Econometrics, Operations research and System theory, Technical University, Vienna = TUW.IO

2. Origins analysis, control analysis and (static) simulation

3. Developing a user friendly computer tool

2.1 Model class

In a first step the model class is specified by verbal modelling and formalised in the flow sheet. This comprises the delimitation of the system from the outside world (surroundings), the list of variables (import, export, internal flow variables), the decomposition into subsystems (compartments, in MFA they are called processes or subprocesses), the description of the interconnections between the subsystems, the a priori knowledge concerning the subsystems such as balancing relations, knowledge of transfer coefficients (i.e. relations between inputs and outputs of a subsystem) or additional linear relations (between the inputs of a subsystem or of the whole system) and finally the classification of the data uncertainty.

In a concrete case study the verbal modelling part is the task of the respective case study group. However, it turned out that feedback between case study and modelling groups is essential for both sides.

A further specification of our model class is given by the assumption that all physical subsystems are balanced (according to the mass conservation law) and that uncertainty is described by a stochastic noise model under the assumption of normally distributed flow measurements.

From a practical point of view the delimitation of the system is often a delicate problem and may be of great importance for the results obtained. For regional material flow models data in space and time may be of interest; here, however, the spatial aspect is neglected. Flow data are defined for time intervals rather than for a time point, therefore the choice of the length of these intervals (balancing units) is important. We only considered the case, which is relevant from a practical point of view, where measurements only from one balancing unit are available; in such a case, as will be pointed out below, a lot of extra prior information is required to obtain reasonable results.

In describing the model class also problems of data availability have to be taken into account.

2.2 Treatment of uncertainty

MFA combines information of different quality to develop a complete picture of the material flows investigated. In principle, there are three categories of data on inputs (imports), outputs (exports) and internal variables: (a) Data from technical measurements (e.g. chemical contents of incineration residues), (b) data from administrative records (e.g. production statistics), and (c) hybrid data from studies done at various times for other purposes (generated by other materials accounting procedures, expert knowledge). Additionally, data may also be available directly on transfer coefficients and on the coefficients of additional linear relations.

Due to measurement errors or incomplete information the mass flow data do not satisfy the principle of mass conservation. Imposing this principle provides additional information about the unobserved true flow values and thus allows for an improvement of the quality of the flow estimates (cf. the discussion in 4.3). Clearly the assessment of the quality of data is an important problem. Therefore it is essential that the generation and composition of data are sufficiently transparent to the modeller. Usually only data of categories (b) and (c) above are available. In such a case it is difficult or sometimes even impossible to assess the quality of data.

In our modelling approach we classify the flow data as follows:

(i) *Measured flows*: Due to measurement errors or discrepancies between different data sources, the data capturing procedure leads to intervals for several flows. By a rough and ready method, we use these intervals to obtain an estimate of the variance by interpreting them as $\pm 2\sigma$ intervals of an appropriate normal distribution. This leads to a stochastic model in order to take uncertainty into account.

(ii) *Exactly known flows*: This is a special case of measured data where the intervals are degenerated to a single value.

(iii) *Unmeasured flows*: No direct information about their true values is available.

The same classification is applied to data on transfer coefficients.

2.3 Data reconciliation and model estimation

We use the following model for material flows (Bauer et al., 1997; Gleiß et al., 1998):

$$\begin{aligned} Mf^{0} &= 0 \\ x^* &= x^0 + u, \quad u \approx \mathrm{N}(0,\Sigma) \\ z^* &= z^0 \end{aligned} \tag{2.1}$$

where f^{0} is the n-dimensional vector of all true, in general unobserved flow variables, x^0 is the n_x-dimensional subvector of f^{0} for which noisy measurements x^* are available, u is noise, z^0 is the n_z-dimensional subvector of f^0 where the measurements are noisefree.

The matrix M is a real matrix which is partitioned as $M = \begin{bmatrix} A \\ T \\ R \end{bmatrix}$

with $A \in \mathbf{R}^{m \times n}$, $T \in \mathbf{R}^{c \times n}$ and $R \in \mathbf{R}^{d \times n}$.

For the formulation of the model class the a priori information and the available data are taken into account as follows:

- Let m denote the number of subsystems. Each row of the matrix A represents the mass balance equation for a subsystem (i.e. the sum of all input flows is equal to the sum of all output flows). Each column of A corresponds to a flow.

- The matrix T represents the c transfer coefficients (TCs) equations, each of which describes an output of a subsystem as a linear combination of the inputs into the subsystem considered. For each subsystem there are as many TC equations as there are outputs from the subsystem (i.e. c equals n minus the number of inputs of the whole system). Note that for each subsystem the TC equations sum up to the corresponding balance equation; these balance equations, however, are already listed separately and correspond to the matrix A.
  If there are not only unmeasured and exactly known but also TCs which are measured subject to noise, then (2.1) is extended by a noise model for these observed coefficients t_{ij}^*:
-

$$t_{ij}^* = t_{ij}^0 + v_{ij} \quad \text{with } E(v_{ij}) = 0 \text{ and known } Var(v_{ij}) = \tau_{ij}^2 \tag{2.2}$$

- The flow data are classified according to the uncertainty of measurement (without distinguishing a priori between inputs, outputs and internal flows of the whole system) as follows:

  a) For some of the true flows there exist measurements x^*, which in general do not satisfy the balance requirements. These flows are called *measured flows*, their measurements are modeled by a normal distribution with (unknown) mean x^0 (the true flow value) and known (assumed) n_x x n_x variance-covariance-matrix Σ (see subsection 2.2).

  b) On the other hand we might know the true values z^0 of n_z flows exactly.

  c) The remaining $n_y = n - n_x - n_z$ flows are called *unmeasured flows*, there exists no direct information about their true values y^0.

- The matrix R represents $d < n - c$ linearly independent additional linear relations between flows, which are linearly independent of the balance and of the TC equations. In many MFA applications, additional linear restrictions on inputs of the whole system or of a subsystem are available, which are not related to mass balance equations. In such a case there is a discrepancy between the notion of a physical input and a system theoretic input.

- There is one kind of a priori information we do not take into account in this approach, namely that both flows and TCs are a priori known to be non-negative. As a consequence negative flow or TC estimates may occur (which may be a hint on misspecification).

An aim of the procedures developed is to find *flow estimates* $\hat{x}$ which approximate the true values x^0 optimally in some sense as well as estimates $\hat{y}$ of y^0 (clearly $\hat{z} = z^0$ holds). These estimates fulfil at the same time the balance equations and take into account the known TC equations as well as the additional linear relations. In this way the optimal use of the a priori information and of the given data in order to improve the precision of the measurements is intended. This will be accomplished by reconciliating the measurements according to their inverse variance-covariance structure. In the case where TCs are measured subject to noise a two-step procedure is applied in order to take their uncertainties into account.

2.4 Origins Analysis and simulation

For various reasons it is interesting to know more about the internal dependencies between different flows of the system under consideration, i.e. not only about the (direct) dependencies between flows incident to the same subsystem (e.g. via TC estimates), but also between flows where one influences the other via all possible directed[2] paths through the system.

The aim of an *origins analysis* (as introduced by van der Voet et al., 1995) is to find a set of input or internal flows (*contributor sets*, see Gleiß et al., 1998), which give a complete physical explanation of a considered flow and which do not influence each other in the physical sense. This procedure is based on the structure of the system represented by the balance equations (matrix A) and on the TCs, which are now fixed at the values of their estimates. In this way one gets a clear quantitative picture of which flows contribute to the considered flow to what extent.

It is important to see that the percentages of contribution are in general not identical to the effect of a modification of the value of a flow within the set, since upstream dependencies are neglected here.

For the investigation of such effects, a different concept has to be considered: With the help of *Control Analysis* (see Gleiß et al., 1998) it is possible to control the system not only by the physical inputs but also by a set of system theoretic inputs (containing also internal and output flows).

Having estimated all flows and TCs, the identification of the model is completed. Based on the identified model, scenario simulations can be performed. A scenario comprises the modification of TC and/or flow values. The effects of the scenarios are calculated by the use of control analysis.

2.5 Limitations of the static model

Our formal analysis of the static case has been restricted to the linear case. The main shortcomings of this analysis are the assumption of an a priori known variance-covariance matrix Σ for the noise and the fact that we neglected the non-negativity restriction on flow- and transfer coefficient estimates.

[2] Directed means along the flows of the system taking into account the flow directions.

3 Dynamic modelling

In MFA dynamics come in via stocks of substances. Typically, dynamic material flow systems consist of several interconnected subsystems, each of which in general has the form shown in fig. 3-1.

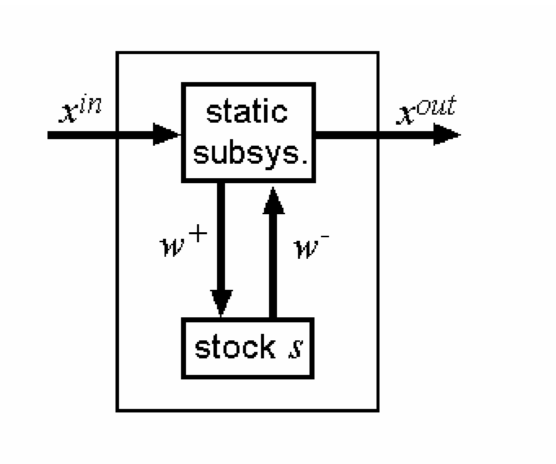

Figure 3-1: Dynamic subsystem

The static part of a subsystem is connected to the rest of the system via the inputs x_t^{in} and the outputs x_t^{out}. If the considered subsystem has a stock, then also w_t^+ and w_t^-, the flow into the stock in period t and the flow out of the stock are an output and an input of the static part, respectively. In any case, the linear relation between the inputs and the outputs is described by so called *transfer coefficients* (matrix Λ):

$$\begin{bmatrix} x_t^{out} \\ w_t^+ \end{bmatrix} = \Lambda \begin{bmatrix} x_t^{in} \\ w_t^- \end{bmatrix} \tag{3.1}$$

where each column of Λ sums up to one, according to the mass balance principle.

With s_t denoting the stock level at the end of period t and $k(z) = \sum_{j=0}^{\infty} k_j z^j$ denoting the transfer function of the stock dynamics, we have for a single stock:

$$\begin{aligned} s_t &= s_{t-1} + (w_t^+ - w_t^-) \\ w_t^- &= \sum_{j=0}^{\infty} k_j w_{t-j}^+ \end{aligned} \tag{3.2}$$

where $\sum_{j=0}^{\infty} k_j \leq 1$ and $k_j \geq 0$.

The objective here is to develop an identification procedure for a general linear dynamic MFA problem. This identification problem in particular consists of a method for data reconciliation and for estimation of the model parameters (transfer coefficients and the parameters determining the transfer functions), of the unmeasured flows and stocks. In addition, procedures for dynamic origins analysis and policy simulation, both based on the identified model, are developed.

In order to find an appropriate model class it is reasonable to specify the transfer function in (3.2) for each stock by an adequate low-dimensional parametrisation. Note that this specification will in general be different for each stock depending on the phenomenon to be described. In the following, three examples are given (based on personal communication with Johan Hedbrant, Linköping Univ., and René Kleijn, CML, respectively):

(i) A proportionally declining behaviour of the stock outflow corresponds to

$$w_t^- = \frac{1}{\tau} s_t \quad \text{i.e.} \quad \begin{cases} k_0 = 0 \\ k_j = \frac{1}{\tau}\left(1 - \frac{1}{\tau}\right)^{j-1} \text{ for } j \geq 1 \end{cases} \tag{3.3}$$

with a single stock parameter τ.

(ii) Modelling an exact lifetime τ of the goods in the stock leads to

$$w_t^- = w_{t-\tau}^+ \quad (\tau \in \mathrm{N}) \quad \text{i.e.} \quad \begin{cases} k_j = 1 & \text{for } j = \tau \\ k_j = 0 & \text{otherwise} \end{cases} \tag{3.4}$$

whereas

(iii) a distribution of the lifetime is given by the model class resulting from

$$w_t^- = \sum_{j=d_1}^{d_2} k_j(\varphi) w_{t-j}^+ \qquad \text{with } \sum k_j \leq 1 \tag{3.5}$$

where the k_j are taken from a truncated, discretised distribution over the truncation interval $[d_1, d_2]$ with parameter vector φ.

Of course, reasonable distributions for the third case have to be specified and alternative descriptions of the stock dynamics will be investigated.

While case (i) is appropriate for environmental stocks, cases (ii) and (iii) describe economic stock behaviour.

The linear model for the whole material flow system is of the form:

$$A_\theta(L) y_t = C_\theta(L) x_t \tag{3.6}$$

where

$$A_\theta(L) = \sum_j A_j(\theta) L^j \text{ and } C_\theta(L) = \sum_j C_j(\theta) L^j \tag{3.7}$$

are lag polynomials (in the lag operator L) for the true internal and output flows comprised in vector y_t and for the true inputs x_t, respectively. The chosen specification for each stock leads to certain restrictions (which correspond to the balance equations of the static case) on the coefficient matrices $A_j(\theta)$ and $C_j(\theta)$.

It is important to note first, that in the case of an exact or distributed lifetime non-zero coefficient matrices $A_j(\theta)$ and $C_j(\theta)$ occur only for certain values of j in accordance with the truncation intervals of the single stocks. Thus also these interval limits (or exact lifetimes, respectively) have to be estimated, if they are not known a priori.
Also note that equation (3.6) represents an exact (deterministic) relation between the true flows.

If both, internal and output flows as well as inputs, are only observed (as y_t^* and x_t^*, respectively) subject to noise (ε_t and ξ_t, respectively)

$$\begin{aligned} y_t^* &= y_t + \varepsilon_t \\ x_t^* &= x_t + \xi_t \end{aligned} \tag{3.8}$$

then there are symmetric errors-in-variables model of the form

$$\begin{aligned} B_\theta z_t &= 0 \\ z_t^* &= z_t + \eta_t \end{aligned} \tag{3.9}$$

where $z_t = \begin{bmatrix} x_t \\ y_t \end{bmatrix}$, $z_t^* = \begin{bmatrix} x_t^* \\ y_t^* \end{bmatrix}$ and $\eta_t = \begin{bmatrix} \xi_t \\ \varepsilon_t \end{bmatrix}$, and where

$$B_\theta(L) = \sum_j B_j(\theta) L^j \text{ with } B_j(\theta) = \begin{bmatrix} -C_j(\theta) & A_j(\theta) \end{bmatrix}. \tag{3.10}$$

In general, not all flows in a material flow system are observed, so that equations (3.8) to (3.10) have to be modified accordingly.
For MFA models it is reasonable to assume

$$\begin{aligned} E(\eta_t) &= 0 \\ Var(\eta_t) &= \Sigma = diag \quad \forall t \end{aligned} \tag{3.11}$$

Analogously to the static model, normality and known variance are reasonable additional assumptions for the noise term.

The non-negativity constraints complete the description of the model class. Thus we arrive at a highly and naturally structured problem.

For the development of an identification procedure by using the concepts and methods of system theory, this particular structure has to be taken into account. The problems of stability, controllability, observability and identifiability have to be analysed.

4 Results

4.1 The static case

For the model class described above, which is sufficiently large to cover a wide range of MFA problems, instruments have been developed to meet the actual demands of MFA. Thereby we made extensive use of the concepts and methods of system theory (Bauer et al., 1997, Gleiß et al., 1998). Thus we are able to give solutions to the following problems:

(i) Optimal use of the information contained in both the a priori information (balance equations, additional linear relations) and the data (flow measurements, transfer coefficient measurements) in order to improve the data quality (data reconciliation)

(ii) Estimation of unmeasured flows

(iii) Estimation of the model parameters (transfer coefficients)

(iv) Detecting the „white spots“ (unmeasured flows, which cannot be uniquely estimated) on the flow sheet of the system.

(v) Making future measurement programs more (cost) efficient by taking additional measurements only at those places detected as parts of an unmeasured cycle or of a cycle containing a non-redundant flow.

(vi) Showing those subsystems where gross measurement errors or missing flows (i.e. flows which have been neglected in the flow sheet) can most probably be expected by application of statistical test routines.

(vii) Understanding the inner structure of the system (e.g. by origins analysis)

(viii) Comparison of different control strategies on the basis of the identified model (control analysis and scenario simulation)

The procedures introduced in section 2 are shown in a schematic way in the following fig. 4-1 (Gleiß et al., 1998):

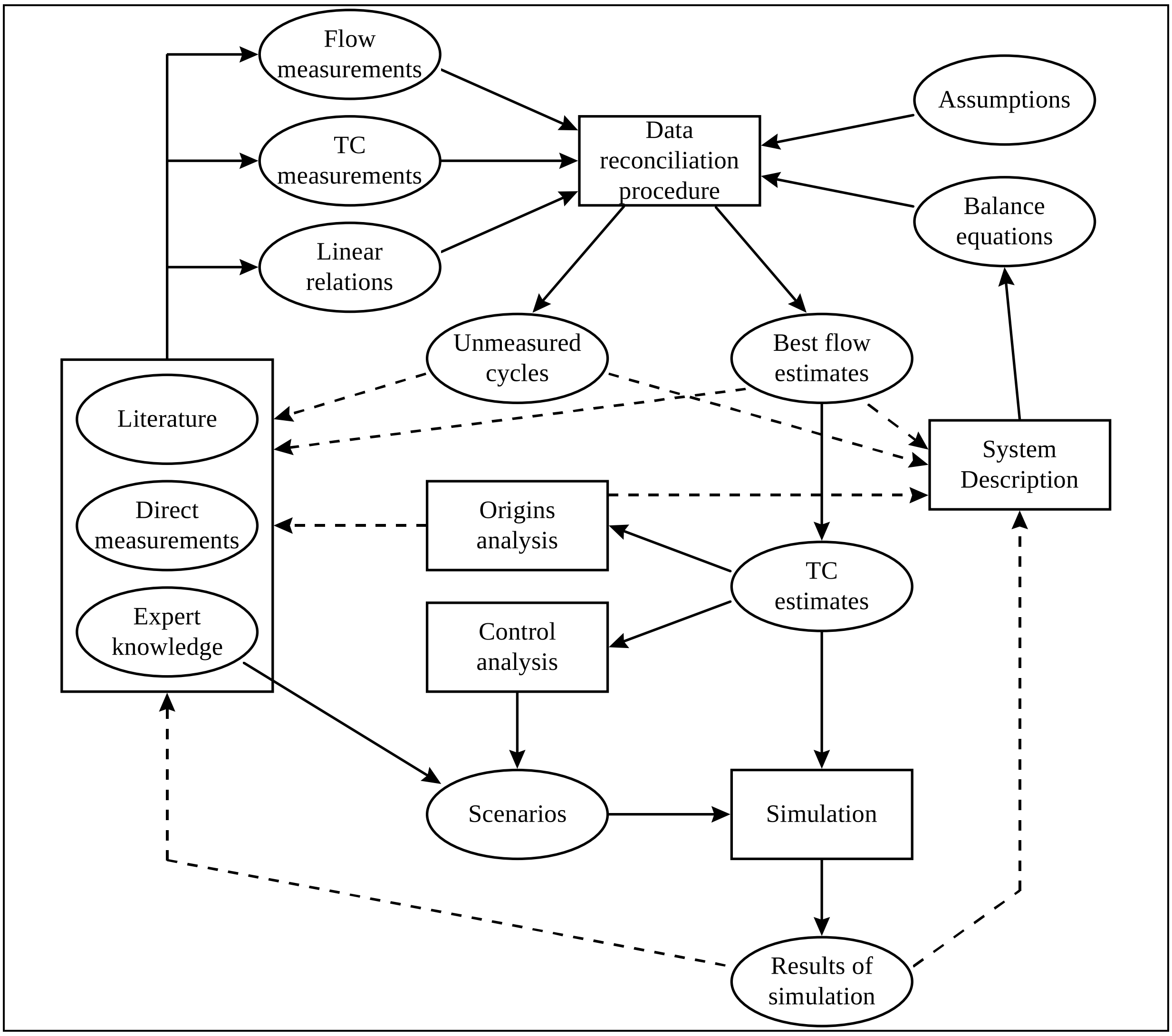

Figure 4-1: Procedures (rectangles) and their in- and outputs (ovals) for identification and simulation of a linear, static material flow system

By the implementation of this mathematical model on the computer as a MATLAB® routine we are able to handle MFA problems (case studies in co-operation with MAc TEmPo partners) of realistic dimensions (see Gleiß et al., 1998). An example of the graphical user interface and the data display is shown in fig. 4-2.

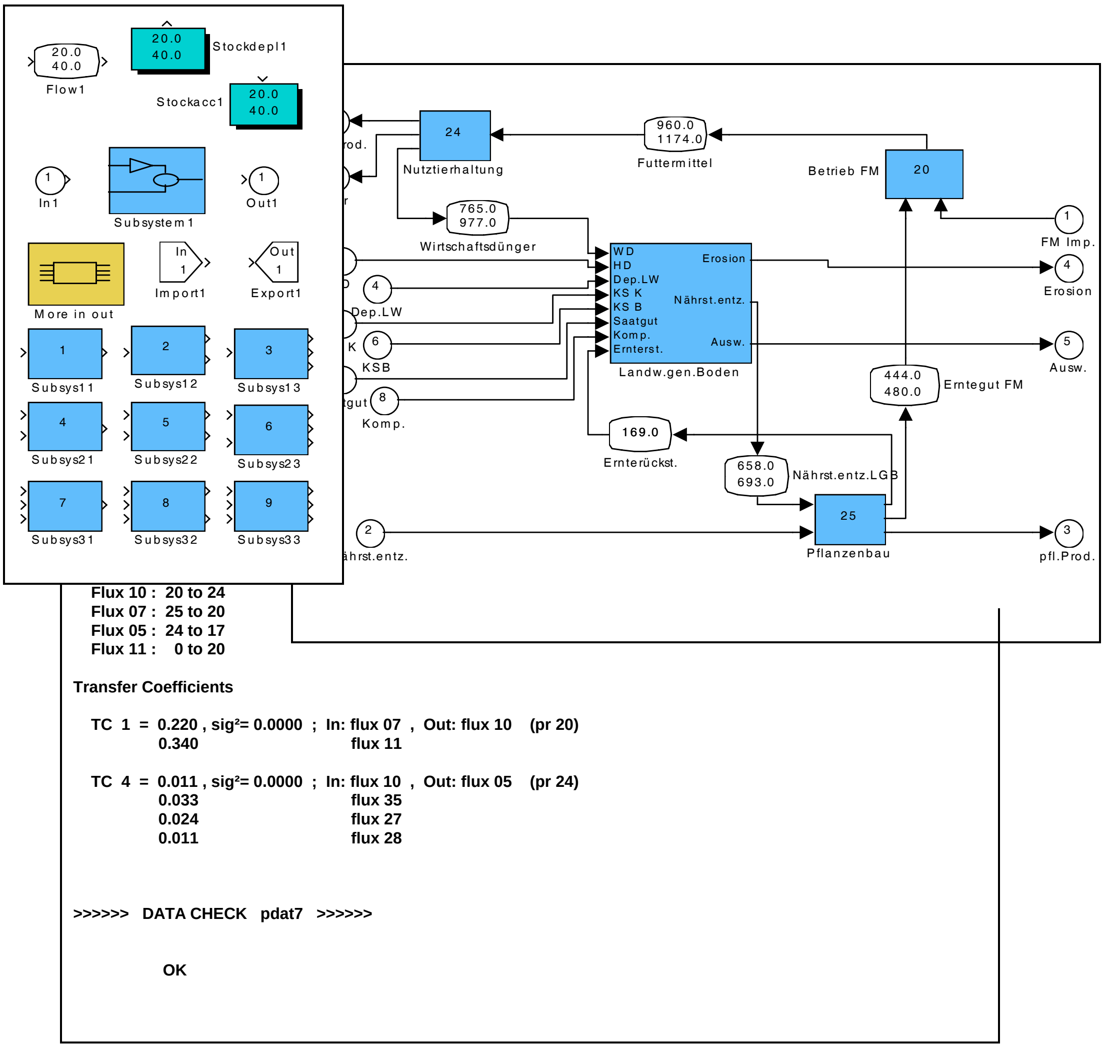

Figure 4-2: Graphical user interface:
Module Library (left window) and example flow sheet (right window);data display (text window).
Data are taken from Glenck et al. (1995).

4.2 The dynamic case

Here, research is still in the initial phase. The first results are concerned with the stability condition and with (necessary) conditions for controllability and observability for a system of stocks of type 1 (see section 3). A great amount of further research is needed.

4.3 What's new?

The principle underlying the approach of the EOS group to model MFA systems is *data driven modelling*, i.e. identifying a model from data taking into account all a priori information. Whereas a priori information such as balance equations is considered also in other MFA models, our approach also incorporates the noise structure of the data (flows and TCs). Linking these two sources of information provides additional information about the unobserved true flow values. Thus an improvement of the quality of the flow and TC estimates is achieved.

Clearly the quality of the results depends on the quality of the measurements (this is the case also for other approaches to MFA). Thus improvement of the accuracy of the measurements is still a major task for future activities. Note, however, that our approach may be of help in doing so.

This is one main difference to other MFA models, where the data uncertainty is not taken into account or where sensitivity analysis or error propagation considerations are performed only a posteriori.

Additionally, we have analysed the problem of unestimable flows (unmeasured cycles in the static case).

All tools developed for system structure analysis or scenario simulation are based on the identified model. These tools include

- *Origins Analysis* (as proposed by van der Voet et al., 1995), which has been extended in order to take also internal contributors to a given target flow into account and which shows their respective percentages of contribution.

- *Control Analysis*, which enables one to control the whole system not only by the physical inputs, but also by any complete selection of system theoretic inputs (consisting of input, internal and output flows of the whole system); thus also reverse causality can be incorporated. Additional linear relations are taken into account, since they reduce the number of system theoretic inputs. The procedure provides the effects of steering the system theoretic inputs on the target flow.

5 Linkage of Material Flow Analysis to Environmental Policy Decisions

The tools (see above) applied to the identified model are useful for environmental policy decisions:

(i) Early recognition by showing the relevant flows, in particular the relevant stock accumulation / depletion.

(ii) Showing the percentage of contribution of input and internal flows to an internal or output flow which is of special interest (origins analysis).

(iii) Showing the effects of modifying transfer coefficients and flow values on a given target flow (control analysis). This helps to analyse where political measures yield their largest effect; thus the selection of reasonable scenarios is supported.

(iv) Static comparative scenario simulation.

6 Conclusions

In our opinion system theory, in particular system identification provides systematic approaches useful for Material Flow Analysis. For MFA a lot of a priori information, e.g. in form of balance equations, is available. For the important case of a static, linear stochastic model we give solutions to the problems of (optimal) data reconciliation, estimation of unmeasured flows and estimation of transfer coefficients. In addition we show which unmeasured flows and transfer coefficients cannot be uniquely estimated from data corresponding to one balancing unit. Finally, origins analysis has been improved and the tools of control analysis and of scenario simulation are presented.

7 Forthcoming activities

The main objective for our future research is to continue the investigation of the dynamic case.

We aim at describing completely the sets in the parameter space, where the properties of stability, controllability, observability and identifiability hold, in an analytic way. Where this is not possible, the use of symbolic computation is planned. We suppose that at least some of these properties are of a generic type here. In addition, we will investigate, if the answers to the problems mentioned above (i.e. conditions for stability etc.) and, as a consequence, the notions themselves have a specific interpretation in models for MFA problems.

For the dynamic case, controllability and observability refer to flows and stocks and, of course, have a temporal dimension; therefore the concepts of origins analysis and control analysis will be extended accordingly.

8 Literature

The following publications of the EOS group have been generated within the MAc TEmPo project:

Bauer, G.; M. Deistler; A. Gleiß; E. Glenck; T. Matyus (1997): *Identification of Material Flow Systems,* Environ. Sci. & Pollut. Res. 2, 105 - 112

Gleiß, A.; T. Matyus; G. Bauer; M. Deistler; E. Glenck; C. Lampert (1998): *Identification of Material Flow Systems - Extensions and Case Study*, To appear in: Environ. Sci. & Pollut. Res.

9 References

Bauer, G.; M. Deistler; A. Gleiß; E. Glenck; T. Matyus (1997): *Identification of Material Flow Systems,* Environ. Sci. & Pollut. Res. 2, 105 - 112

Gleiß, A.; T. Matyus; G. Bauer; M. Deistler; E. Glenck; C. Lampert (1998): *Identification of Material Flow Systems - Extensions and Case Study*, To appear in: Environ. Sci. & Pollut. Res.

Glenck, E.; C. Lampert; H. Raeissi; P.H. Brunner (1995): *Phosphorbilanz des Kremstales* (in German). Institut für Wassergüte und Abfallwirtschaft, TU Wien

Voet, E. van der; R. Kleijn; L. Van Oers; R. Heijungs; R. Huele; P. Mulder (1995): *Substance flows through the economy and environment of a region- Part 2: Modeling*. Environ. Sci. & Pollut.Res. , no. 3, pp 137-144.

ANNEX 5 to SUMMARY REPORT
Report of the contractor EAWAG.RWM

SYNOIKOS

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1 Objectives

The metropolitan areas of industrialised nations have turned into urban networks with a dense population of several hundred inhabitants per square kilometre and with high anthropogenic energy and material fluxes. Their metabolism, which is interrelated with the world economy, is mainly dependent on fossil energy carriers. No validated evaluation models are currently available on the sustainable development of such urban regions[1]. There may be a global consensus on guiding principles, however, the consequences with regard to the cultural changes have not yet been assessed on a regional level [Imboden and Baccini 1996, Oswald and Baccini 1996, Baccini 1996].

One of the key issues associated with sustainable development focuses on the metabolism of urban systems. The Swiss Lowlands, situated between lake Geneva and Lake Constance, comprise a typical urban system of the developed world. Within this system, a smaller region (see Figure 1) serves as case study to answer the following questions:

a. What are the main evaluation criteria for a sustainable development of an urban system ?

b. How can these criteria be applied to resource management of the geogenic and anthropogenic ecosystems within the region (e.g. forests, surface water, agricultural land) ?

c. What are the most promising scenarios to raise the present urban systems to a standard that would meet the criteria of *sustainability* ?

[1] For a definition of "sustainable development" see page 3.

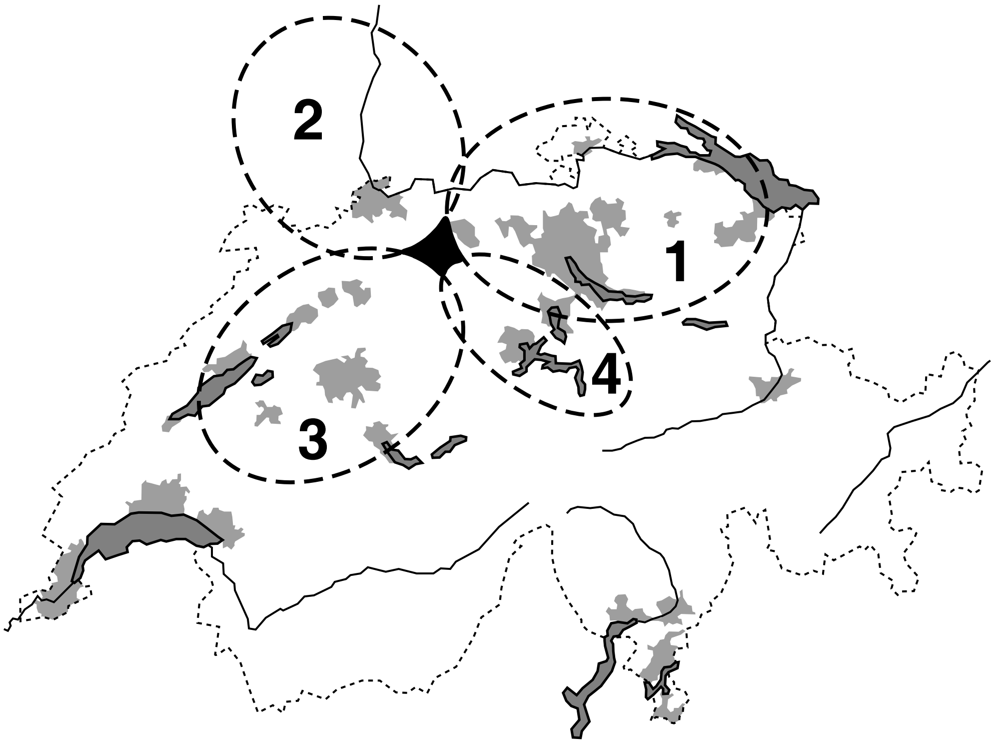

Fig. 1: Location of the study region.

The Swiss Lowlands are situated between Lake Geneva (in the south-west) and Lake Constance (in the north-east). Each of the circles is a metropolitan region. Circle 1-Zurich; Circle 2-The Upper Rhine Region and Basel; Circle 3-The Bernese Region; Circle 4-Lucerne. The region studied, the "Kreuzung Schweizer Mittelland", is the area in the centre of the four intersecting circles.

To evaluate the sustainability of the metabolism of the Swiss Lowlands, assumptions are made to evaluate any urban system. It is presupposed that the metabolism of any urban system is sustainable if [Baccini 1997]:

– More than 80 per cent of the demand for essential "mass goods" such as water, biomass, construction materials (e.g. stones), and energy carriers, can, on a long term, be met autochthonously. The degree of self-sufficiency, arbitrarily chosen with respect to a set of essential materials, determines the ecologically defined border of an urban system. Self-sufficiency by itself may not be generally accepted as a criterion for sustainable development. However, it is chosen in the SYNOIKOS project with respect to the long-term use of "mass goods" because of their future global scarcity. In this context it is assumed that self-sufficiency on a regional level will improve a region's future position in negotiations concerning the interregional (or global) distribution of resources and eventually encourage equal distribution on a global scale.

– As long as the first criterion is not fulfilled and for the remaining supply of "mass goods" through interregional exchange their demand is met by the "external market" to the extent that the global resource capitals are not reduced significantly.

– The outputs (emissions) have no detrimental impacts on future generations. No environmental spheres (hydrosphere, atmosphere, lithosphere) may be used as sink for anthropogenic fluxes to the extent that these spheres or parts of them become hazardous for humans or the biosphere.

The following three subsystems were chosen to apply and, thus, evaluate these criteria: the regional material management systems of *water, biomass* and *construction materials* (in combination with energy carriers). Investigation of the management of these three "mass materials" in the study region will allow to establish methodologies for the analysis of the metabolism of the different types of urban developments (e.g. by scenarios). The scenarios comprise a time period of about 60 years (two generations).

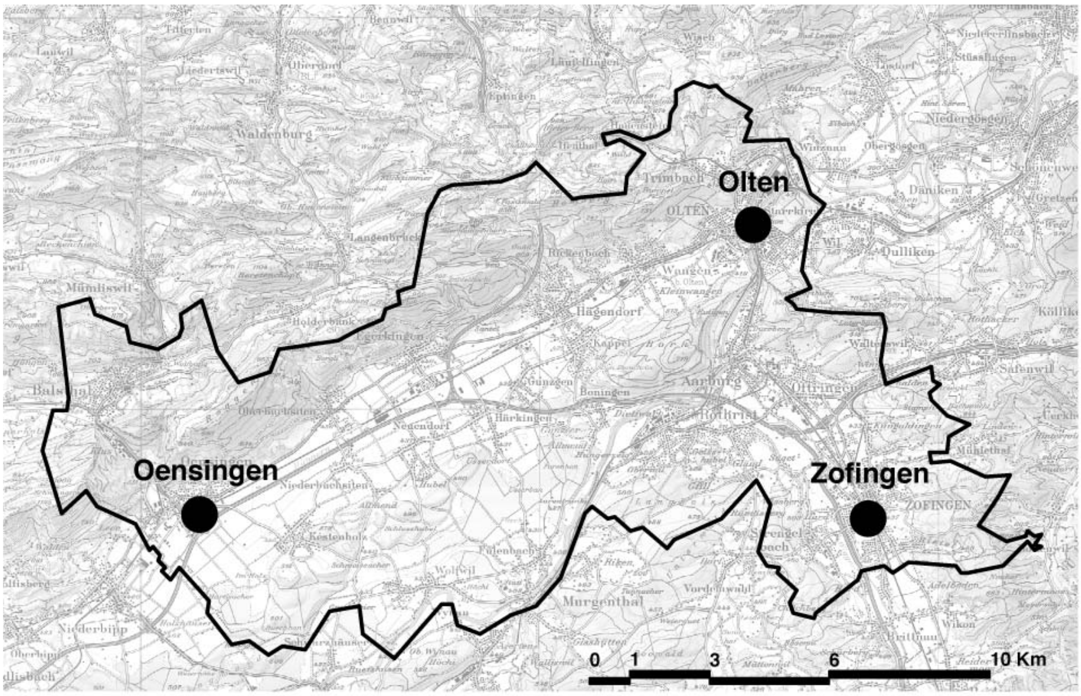

Fig. 2. The KSM study region.

The region numbers 82,000 inhabitants and covers an area of 160 km^2. 41% is made up of forests, 39 % of agricultural land and 18 % of settlements. The area comprises 21 municipalities. The small towns of Oensingen, Olten, Aarburg, and Zofingen are its regional centres. The river Aare runs across the region and forms the border between the cantons of Solothurn and Aargau. The regional environmental policies (e.g. local programmes for saving energy) are made by the 21 municipalities, the two cantons (e.g. regulations pertaining to the use of gravel), and the Confederation (e.g. legislation on air pollution). No political institution acts in the interest of the KSM region which forms a geographical "whole".

This study is conducted in a region called "Kreuzung Schweizer Mittelland" (KSM) (see Figure 2). This region was originally defined by the SYNOIKOS project and can be characterised as:

- An urban system due to its population density (520 inhabitants per km^2).
- An average region in the Swiss Lowlands (e.g. land use, lifestyle).
- An area in need of development (e.g. exposed to transit traffic, loss of a visible local identity, insufficient political institutions).

The results of the transdisciplinary project SYNOIKOS, combining architecture, city planning and regional material management, are published in Baccini and Oswald 1998. Conceptual arguments with regard to a sustainable development of the Swiss Lowlands are presented in Imboden and Baccini 1996. In the following the emphasis is laid on three aspects:

1) the **metabolic phenomenology of the three goods water, biomass (timber) and construction material (gravel and energy)** and the consequences with regard to their future use,

2) the **application of an economic-ecological model for residential buildings** to implement "sustainable resource management objectives" in political decisions,

3) **first evaluations of substance flow analysis as a tool in political decision processes** for regional resource management, on the basis of two case studies.

2 Methodology

Material Flux Analysis (MFA) is a method to determine, describe and analyse the metabolism of an anthropogenic system (e.g. a region or industry). It investigates the fluxes of different materials through a defined space within a certain time. The method is mainly based on a natural science approach [Baccini and Brunner 1991 and Baccini and Bader 1996]. The method applied uses the following steps:

A. Assessment of the status-quo in a material management system

- Systems analysis: definition of a system border, processes and materials (see 2.1).
- Measurement/assessment of material fluxes, stocks and element concentrations (see 2.2).
- Mathematical description and calculation of the material fluxes within the entire system (see 2.3).
- Schematic presentation and interpretation of the results (see 3.1).

B. Evaluation of future material management strategies

- Choice of a suitable model specification and establishment of the model equations (see 3.1).
- Application of the model, e.g. for scenario calculations (see 3.1).

2.1 Systems Definitions

Geographical boundaries of the subsystems *water*, *biomass* and *construction materials/energy* are defined by the political boundaries of the 21 municipalities. The present state of materials management is assessed on the basis of data over a time span of one year. The following systems are defined:

2.1.1 Water Management System

Seven processes are defined to describe the water management system of the KSM (see Figure 3):

Soil. The soil layer between the surface and the various aquifers in the region. A large amount of precipitation evapotranspirates when entering the soil, and only a smaller amount flows into the aquifer (leachate) or the sewers (stormwater). As almost no irrigation takes place in the region the agricultural use of water is directly connected with this process. Water fluxes in agricultural products are neglected.

Aquifer. The region has various groundwater aquifers which are regarded as a single process. Leachates, losses from the water supply system and groundwater inflows enter the process. Its main outputs are groundwater which is pumped by the water supply system or directly by households, industry and trade, groundwater outflows to neighbouring systems and the net exfiltration towards the surface water.

Water supply. The water supply system is mainly run by the municipalities. They take groundwater from the aquifer and distribute it to households, industry and trade.

Sewers. Sewer infiltration water (sewer inf. water), wastewater and stormwater are collected in the sewers and transferred to sewage treatment plants (raw sewage) and to the surface water (overflow).

Sewage treatment. The water collected in the sewers is treated in the sewage treatment plants and discharged into the surface water (treated sewage). By-products are digester gas (air emission) and sewage sludge (subjected to further treatment or spread on agricultural soil).

Households, industry and trade (households, ind. & trade). Drinking water and groundwater are consumed by households, industry and trade. The used water is discharged into the surface water (process water) or into the sewers.

Surface water. This process includes all the rivers running through the region, including the ponds and channels. The *Aare*, *Duennern*, *Wigger*, and *Pfaffnern* are the main rivers of the region, and the “Chrebskanal” the main channel.

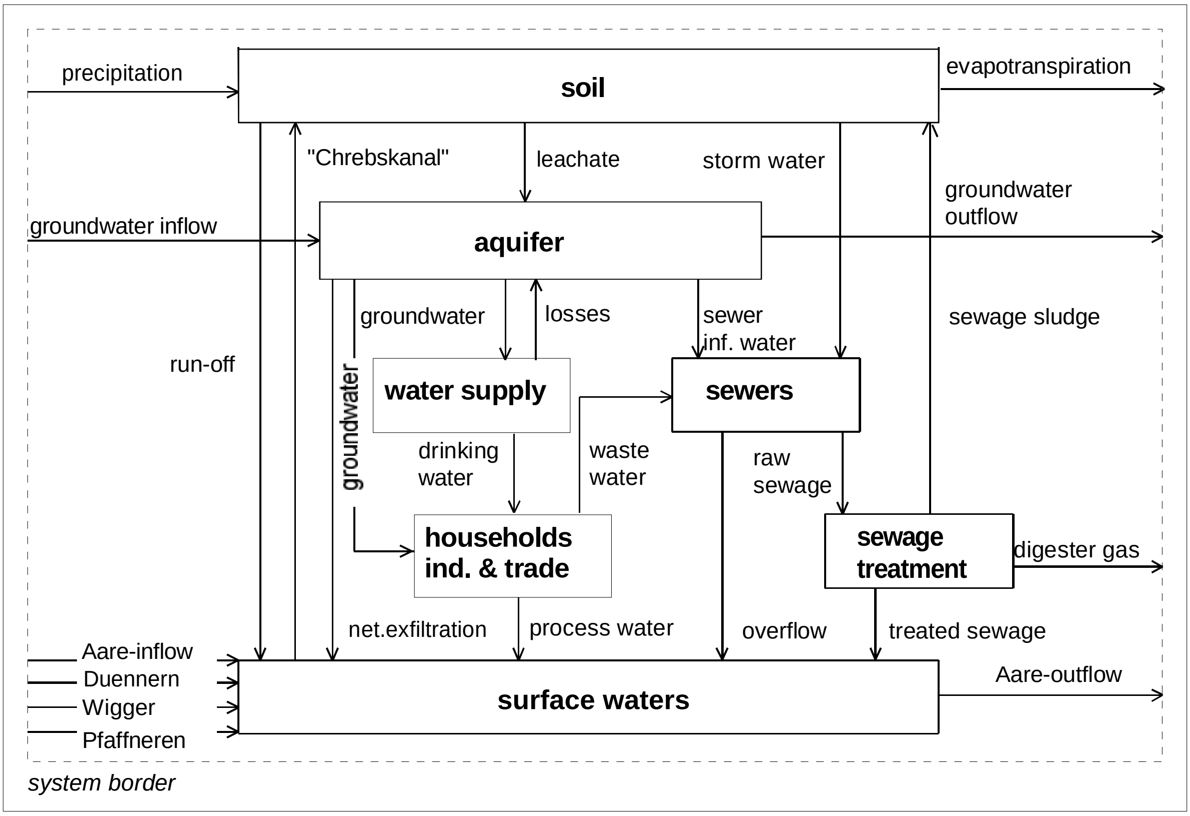

Fig. 3. Simplified water management system for the KSM region.

2.1.2 *Biomass Management System Exemplified by Timber and Derived Products*

Investigation of timber and derived products is given as a general example for biomass management. The system is described by the following five processes:

Forestry. This process comprises all forests (as stock of standing timber) within the KSM region and the means to maintain their timber production. The net inflow of air is the only input considered (representing the growth of wood).

Production and trade of timber products (p. & t. of timber products). In this process, all kinds of products are manufactured from logs (from local forests or other regions) and distributed to the consumers (wood products). A by-product of this process (wood waste/production and fuel wood 2) is distributed to the *production and trade of paper products* or *incinerated and subjected to waste management*.

Consumption of timber products. Timber products are consumed by households, industry and trade. They are transferred into the stock (e.g. building material), to incineration and waste management (wood waste/products) or returned to the production of timber products (recycled timber).

Production and trade of paper products (p. & t. of paper products). In this process, paper products are manufactured from pulpwood (from the local forests or other regions) and distributed to the consumers (paper products). A by-product of this production (lignin) is transferred to incineration and waste management.

Consumption of paper products. Paper products are consumed by households, industry and trade. They are transferred to incineration and waste management (waste paper) or returned to paper production (recycled paper).

Incineration and waste management. In this process, various material flows of timber and derived products are burned or treated otherwise and transformed into emissions (fuel wood 1 and 2, wood waste/products, lignin and waste paper).

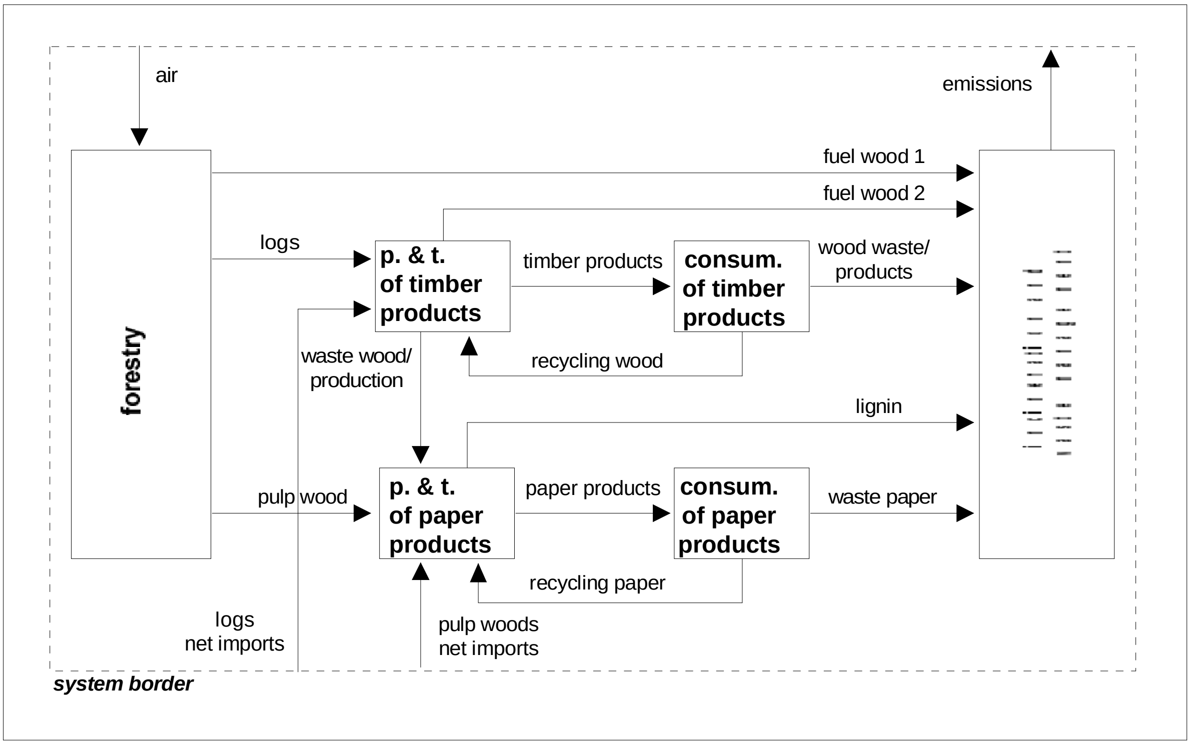

Fig. 4. Simplified management system for timber and derived products in the KSM (the abbreviation p.&t. stands for production and trade).

2.1.3 *Construction Materials Management System (In Combination with Energy)*

To analyse the material management system for construction materials, only the bulk material fluxes such as gravel, sand and concrete are selected. All energy flows related to the processes which transform, transport or store these fluxes are included. The system is described by the following six processes:

Distribution of energy. This process comprises all activities pertaining to the distribution of energy carriers (fossil fuels, electricity etc.). No differentiation is made between the various energy carriers but considered them as one energy flux which is imported into the system from neighbouring regions. Energy is transferred to the energy consuming processes (construction, old residential buildings, optimised residential buildings, new residential buildings).

Construction. New residential buildings are constructed in concrete and consisting mainly of gravel and sand. The *construction* process includes the production of building materials as well as building construction. In this process, all transformed energy is considered as waste heat. The output flux *"concrete"* represents the product of the process.

Old residential buildings. This process includes maintenance and operation of all residential buildings in the KSM region to be built by the year 2000. It is assumed that no further construction material is needed for maintenance. The process is a source for building material (concrete) as old residential buildings are demolished. A possible change of old residential buildings to optimised residential buildings is represented by a flux of concrete. This building material is reused as recycling material (via the *demolition* process). In old residential buildings, heating energy is transformed into waste heat.

Optimised residential buildings. This process comprises maintenance and operation of all residential buildings within the KSM region in which the consumption of heating energy is reduced by technical measures over time (after the year 2000). It is assumed that no new building material (concrete) is necessary in these technical measures. The process is also a source of building material (concrete) as optimised residential buildings will eventually be demolished. This building material is reused as recycling material (via the *demolition* process). In optimised residential buildings, heating energy is transformed into waste heat.

New residential buildings. This process includes maintenance and operation of all residential buildings constructed after the year 2000 in the KSM region. It uses building materials (concrete). It is assumed that no new buildings are demolished during the studied period. Heating energy is transformed into waste heat in new buildings.

Demolition. Building materials from old and optimised residential buildings are recovered via demolition and sorting. It is used in the *construction* of new buildings or leaves the system (as waste).

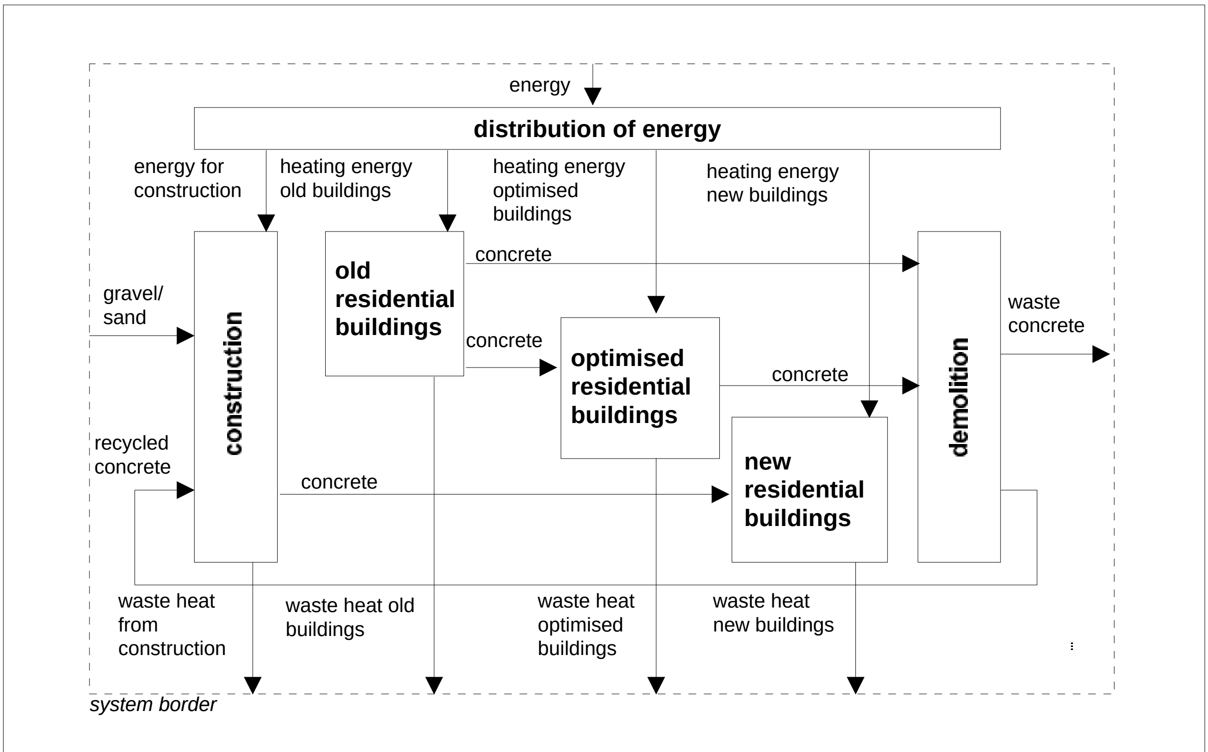

Fig. 5. Simplified management system for construction materials in combination with energy in the KSM region.

2.2 Assessment of Material Fluxes and Stocks

Based on the systems definitions in Figures 3, 4 and 5, the data was classified into:

a. Already measured data from national, regional and local statistics.

b. Data that can be assessed from the measured data on the basis of the mathematical description of the system applied to calculate the best estimates for the variables (by using a least square fit [Baccini and Bader, p. 126ff]).

In the Synoikos project, data was not directly measured in the region.

2.3 Mathematical Description and Modelling

The mathematical description of MFA systems allows data analysis and development of monitoring concepts and forecasts. Each model is specific to the system chosen. Development of a mathematical model for a specific system comprises the following steps [Baccini and Bader 1996]:

1. Complete description of the system using system variables determined by the system analysis. The system variables fully describe a MFA system in time and space. The variables of a MFA system are the following:

   $M^{(j)}(t)$: amount of material in V_j

   $A_{rj}(t)$: material flow from V_r to V_j

   V_r : selected balance volume (process)

2. Determination of the set of general equations (balance equations) describing the general interactions and valid for all systems. For materials, elements and energy they state that the input flux equals the output flux plus the flux to or from the stocks. Each balance volume Vj can be described with the following general equation.

$$\frac{dM^{(j)}}{dt} = \sum_r A_{rj} - \sum_s A_{js}$$

3. The general mathematical description is applied to data simulation (e.g. calculating the best estimates) and to modelling.[2]

4. Model specification is the base for modelling. It describes the characteristics of the system in a mathematical form by defining model equations. To develop a model the interactions between the various good flows and stocks and their dependencies on external parameters are analysed. On this basis the specific model equations which describe the system variables as a function of the system parameters is chosen. The model can be applied to develop measurement programmes, monitoring concepts and study scenarios for future development.

[2] A different approach of data simulation is introduced in Annex 4.

5. The computer software SIMBOX [Bader und Scheidegger 1995] supports the set-up of material management systems, allows statistically based data evaluations, sensitivity analysis, scenario calculations and flexible visualization of the results.

For applications see e.g. [Bader and Baccini 1997], [Baccini and Bader 1996] and [Binder 1997].

3 Results and Discussion

3.1 Regional Material Management

The estimated current (1990 or 2000) material fluxes and stocks in the material management systems for water, biomass and construction materials are based on Figures 3, 4 and 5. Regarding the material management systems for biomass and construction materials, a material management model was developed which was used to calculate scenarios [Baccini and Bader 1996]. The following results were obtained.

3.1.1 Water Management

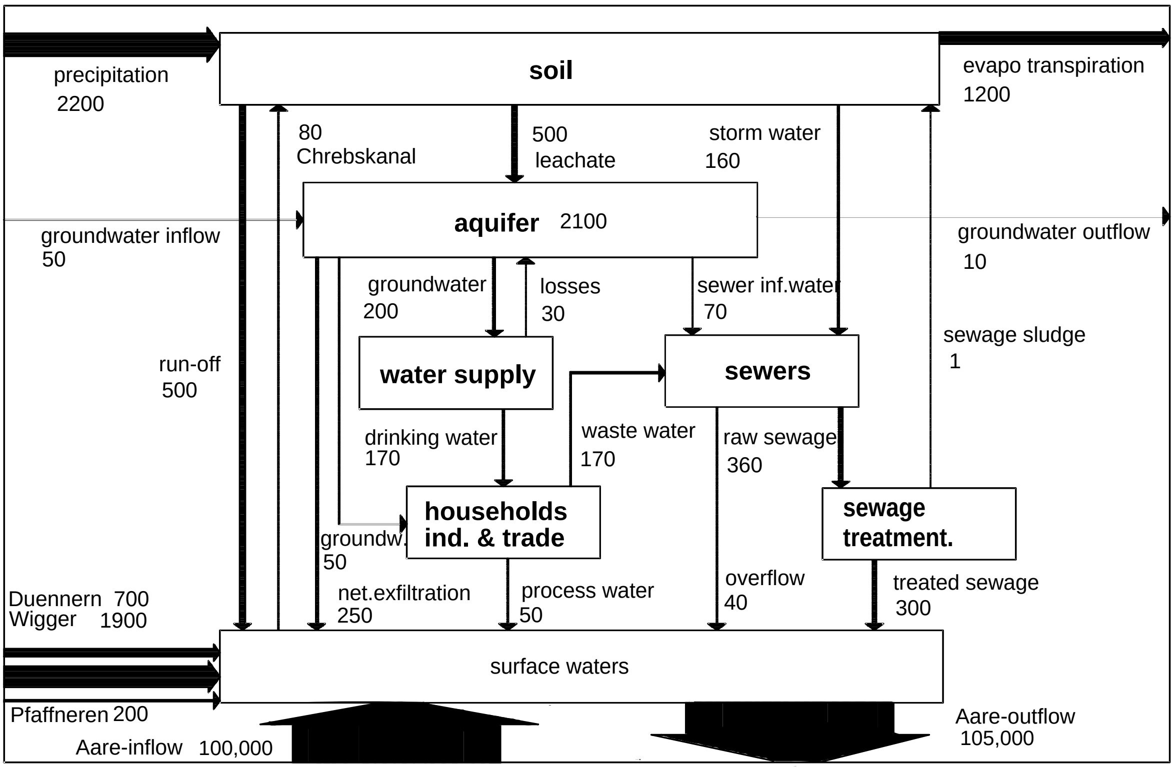

Fig. 6. Water management system for the region KSM in the Swiss Lowlands, Project Synoikos [after Henseler in Baccini and Oswald 1998]. The flux units are m^3 water per capita and year.

The simplified water management system (Fig.6) shows the following quantitative characteristics:

- The surface water form the dominant flux, due to the river Aare which flows through the region. It is responsible for 99% of the annual turnover.
- Approximately 20% of the regional net precipitation is needed to cover the demands of the anthroposphere.
- The water supply system is a technically well developed network which allows a flexible distribution of drinking water. It depends 100% on the regional groundwater reservoir.
- The annual rate of groundwater consumption is about half the annual rate of groundwater input from precipitation, filtered mainly by agricultural soil and forests.

The qualitative aspects can be summarised as follows:

- More than 95% of the used water is processed through over sewage treatment plants. The treated waters are directed into the surface waters.
- The main surface water (the Aare), due to its high dilution capacity, is not a good indicator for metabolic processes in the regional water system.
- Measurements of groundwater composition since 1954 show a slow but steady decrease of quality (e.g. increase of nitrate concentration from 10-15 mg/l to 25 -30 mg/l). This is mainly due to the agricultural activity in the drainage area.

The following two main conclusions can be drawn:

i. An appropriate hydrological model for the regional water management system is still lacking. Such a model is indispensable to evaluate different scenarios of water management.

ii. The increase of nitrate concentrations indicates that the use of groundwater does not meet the criteria of "sustainability".

3.1.2 Biomass Management exemplified by Timber and Derived Products

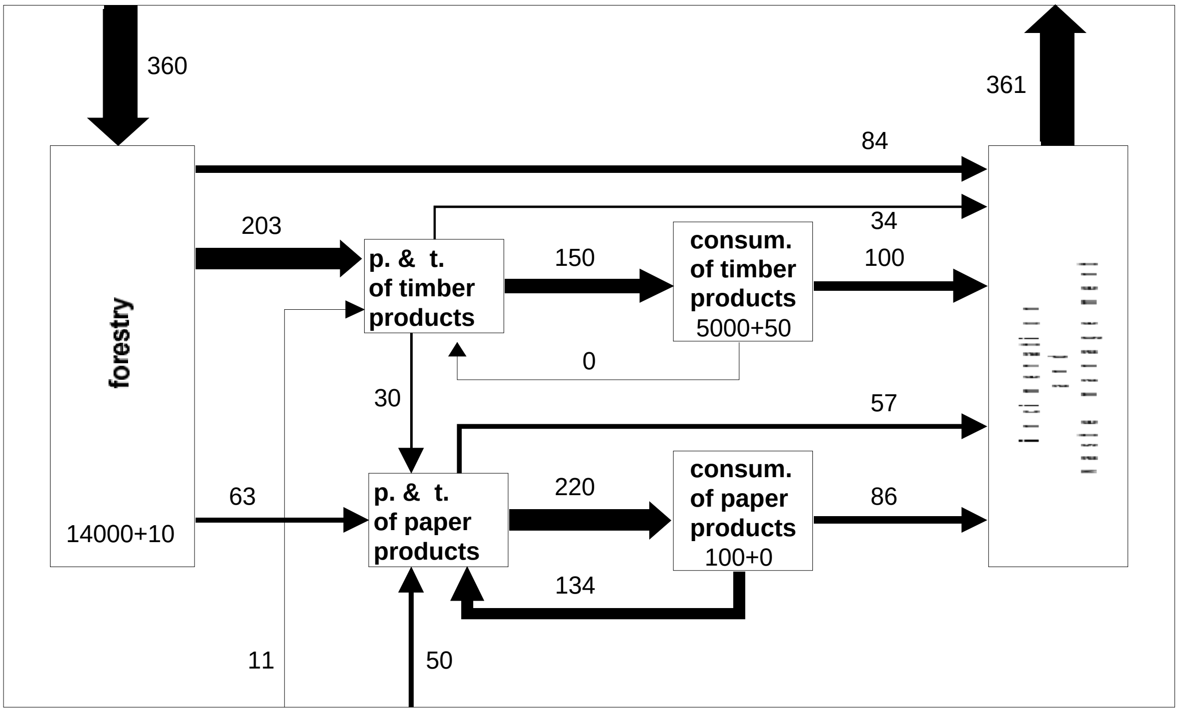

Fig. 7. The biomass management system for the KSM region of the Swiss Lowlands in 1990 (timber and derived products are given as an example). The flux units are expressed in kilogram dry matter per capita and year. The stock units are expressed in kilogram dry matter per capita [Müller 1996]. The abbreviation p.&t. stands for production and trade.

The investigation of biomass management focusses on the first criteria for regional sustainablity: the degree of self-sufficiency. The simplified materials management system for timber and derived products (Fig. 7) reveals the following characteristics:

- The largest timber stock in the region is standing timber in the forests (14 tons of dry matter per capita). The timber stock in the buildings (as a component part of building material) is three times smaller (5 tons of dry matter per capita). The stock of paper is two orders of magnitude smaller (0.1 tons per capita).
- The stocks of standing timber (forests) and of wood as building material component (buildings) are still growing slightly (0.1 and 1 per cent per year).
- The mean residence time of materials in the *consumption of paper products* is less than one year whereas this time span covers a period from 10 to 100 years in the processes of *consumption of timber products* and *forestry*.
- The sales volumes of timber and paper products (in mass units) are in the same order of magnitude. Consumption of raw materials and amount of waste paper are decreasing due to paper recycling. No recycling system has yet been established for wood waste.
- Forestry in the KSM region produces three to four times more logs than pulpwood. The region is 85 % self-sufficient.

Based on the status quo analysis the following consulsion can be drawn:

i. At the end of the 20th century, wood is no longer a scarce resource in many industrialised countries (the degree of self-sufficiency amounts to 85 % with a high level of consumption). However, the question relating to the future role of wood as renewable resource remains unanswered.

In order to get a better understanding of the future role of wood as renewable resource two scenarios examine the effects of consumption changes on the regional wood balance and on the degree of self-sufficiency. They show the following results:

Scenario 1. *Twice as much paper consumption:*

Paper consumption can be doubled with the region's own wood resources if the paper recycling rate is raised from 61 % to 87 % (see Figure 8).

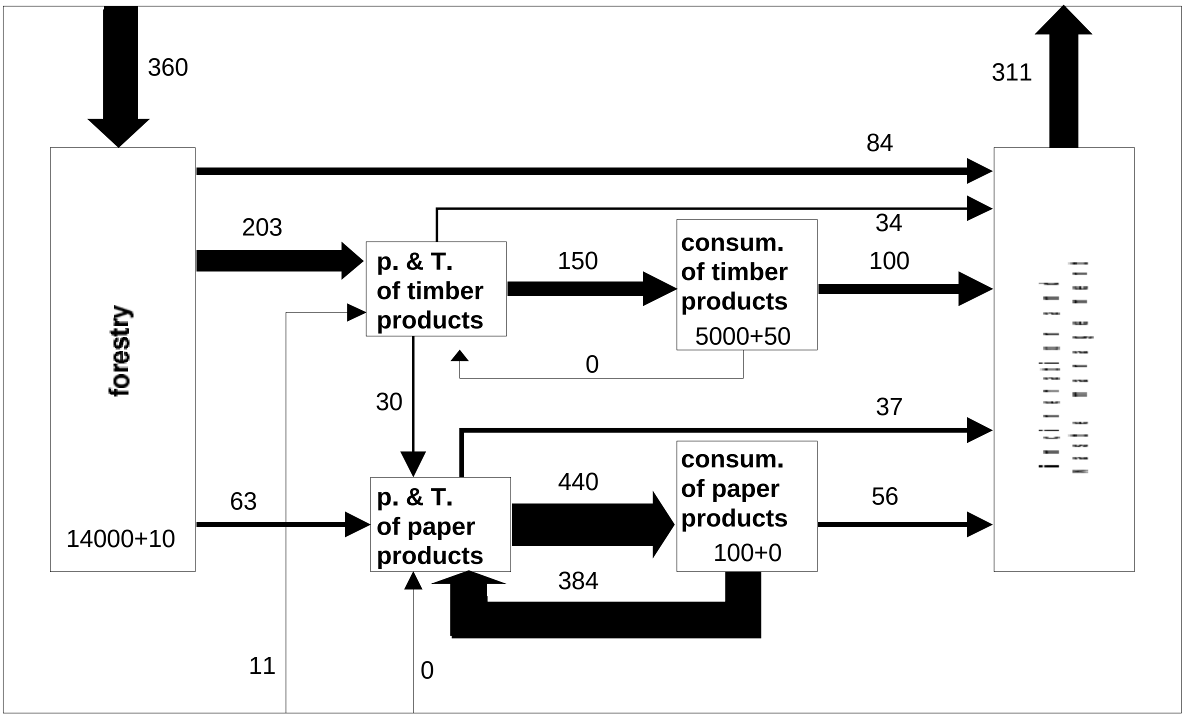

Fig. 8. Fluxes of timber and derived products with twice as much paper consumption and an increase in recycling rate from 61 to 87 per cent. The flux units are expressed in kilogram dry matter per capita and year. The stock units are expressed in kilogram dry matter per capita [Müller 1996]. The abbreviation p.&t. stands for production and trade.

Scenario 2. *Increase in wood content in buildings up to the 1900 level*

If the wood content in buildings is raised to the level of 1900, the degree of self-sufficiency would drop to 40 %. Even if 100 % mature stand are recycled, the degree of self-sufficiency could, for the time being, only be raised to 45 % (see Figure 9). This phenomena occurs due to a delayed output in the process of *consumption of timber products*.

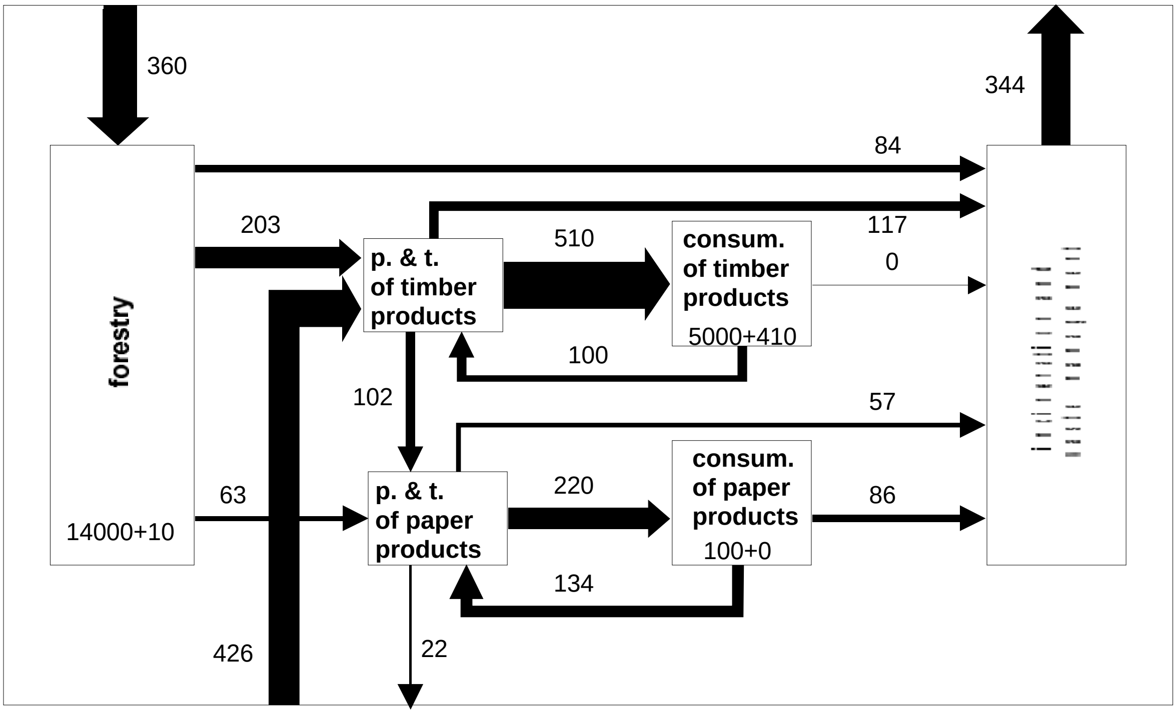

Fig. 9. Fluxes of timber and derived products with an increase in the wood content of buildings up to the 1900 level and a recycling rate of 100 %. The flux units are expressed in kilogram dry matter per capita and year. The stock units are expressed in kilogram dry material per capita [Müller 1996]. The abbreviation p.&t. stands for production and trade.

The scenario calculations support the following hypothesis

ii. Two scenarios on the effects of consumption changes showed that timber rather than paper production should be strongly oriented towards regional forestry. Sustainable forestry practice is itself insufficient to attain a sustainable regional management of wood. A fair balance between production, processing, consumption, and disposal of wood is, therefore, additionally required.

3.1.3 Construction Materials Management (In Combination with Energy)

The analysis of the region's construction materials management system also focusses on the region's degree of self-sufficiency (first criteria for regional sustainablity). The simplified material management system for construction materials and energy (Fig. 10) shows the following characteristics:

– The highest energy consumption is used to heat old residential buildings (in 1990, 30 % of the total energy consumption in Switzerland was used to heat residential buildings). The amount of energy used for construction is one to two orders of magnitude smaller.

– 3.5 % of all old residential buildings are optimised annually, however, almost no buildings are demolished. The stock of construction materials in new residential buildings grows by 1 ton per capita and year. Consequently, the overall stock in residential buildings grows at an annual rate of 1 to 2 percent.

– The amount of recycling material is neglectable (1 % of the annual consumption of construction materials).

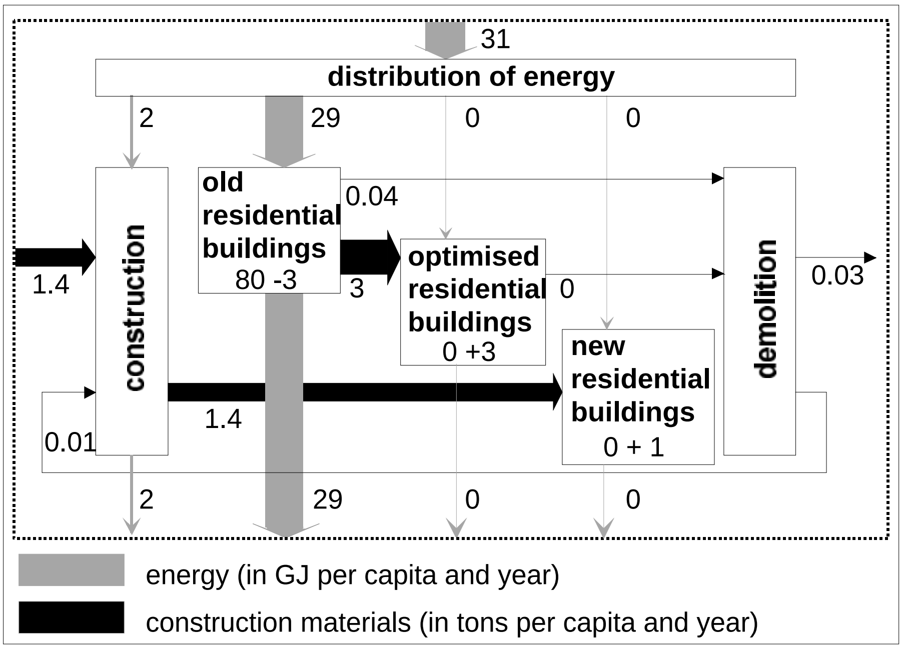

Fig. 10. Fluxes of energy and construction materials (gravel and sand) estimated for the year 2000 in the KSM region. The flux units are expressed in gigajoule (energy) and tons (construction materials) per capita and year. The stock units are expressed in tons per capita [Redle and Baccini 1997].

The findings of the status quo analysis support the following hypothesis:

i. For the next two generations, the key factor associated with "sustainable management" of residential buildings is the energy demand for their operation. The region's energy demand which is caused by operating residential buildings can not be covered by resources available within the region's boundaries. However, the region's demand for construction materials can possibly be covered to a large extend by recycling demolition wastes from the current building stock in future.[3] If recycling technologies are developed and applied according to standards of environmentally sound production neither the quantity nor the quality of the stock of construction materials will be a problem in the future.

[3] The case study of the City of Vienna shows that the ressource potential in the building stock can also be much smaller in urban systems.

The future development of the region's construction materials management system should aim at a high degree of self-sufficiency for both construction materials and energy. Three scenarios examined the effects of different management strategies on the volume of residential buildings and energy consumption:

Scenario 1. *Business as usual.* If the settlement area continues to grow at the current rate, the energy consumption may slightly decrease for about 30 years as more efficient heating systems are installed. In 2030, however, the process of optimisation is completed and the effects of growth become dominant. Thus, energy consumption starts to rise again. Gravel consumption remains at today’s level.

Scenario 2. *Save gravel scenario.* If the building volume is preserved by improved house techniques (optimisation), energy consumption can, on a long-term, be reduced to more than half of today’s consumption. No gravel is consumed in this scenario.

Scenario 3. *Save energy*. If all the buildings are raised to the highest available standard of energy optimisation (total exchange of stock in 50 years), energy consumption is reduced to 10 % of today’s consumption. Gravel consumption is decreased by 40 % (compared to the present level) as the material stock in residential buildings is recycled.

Figure 11 shows the results of the scenario calculation.

The comparison of the three scenarios leads to the following main conclusion:

ii. The concept of a society’s energy policy (which is committed to sustainable development) must be based on the goals of a long-term settlement policy. As the system's energy demand is determined by the existing stock of residential buildings its future development depends upon the future development of the settlement area. A significant reduction of energy consumption can only be reached if the stock of residential buildings stops growing and the existing buildings are raised to the highest available standard of energy optimisation.

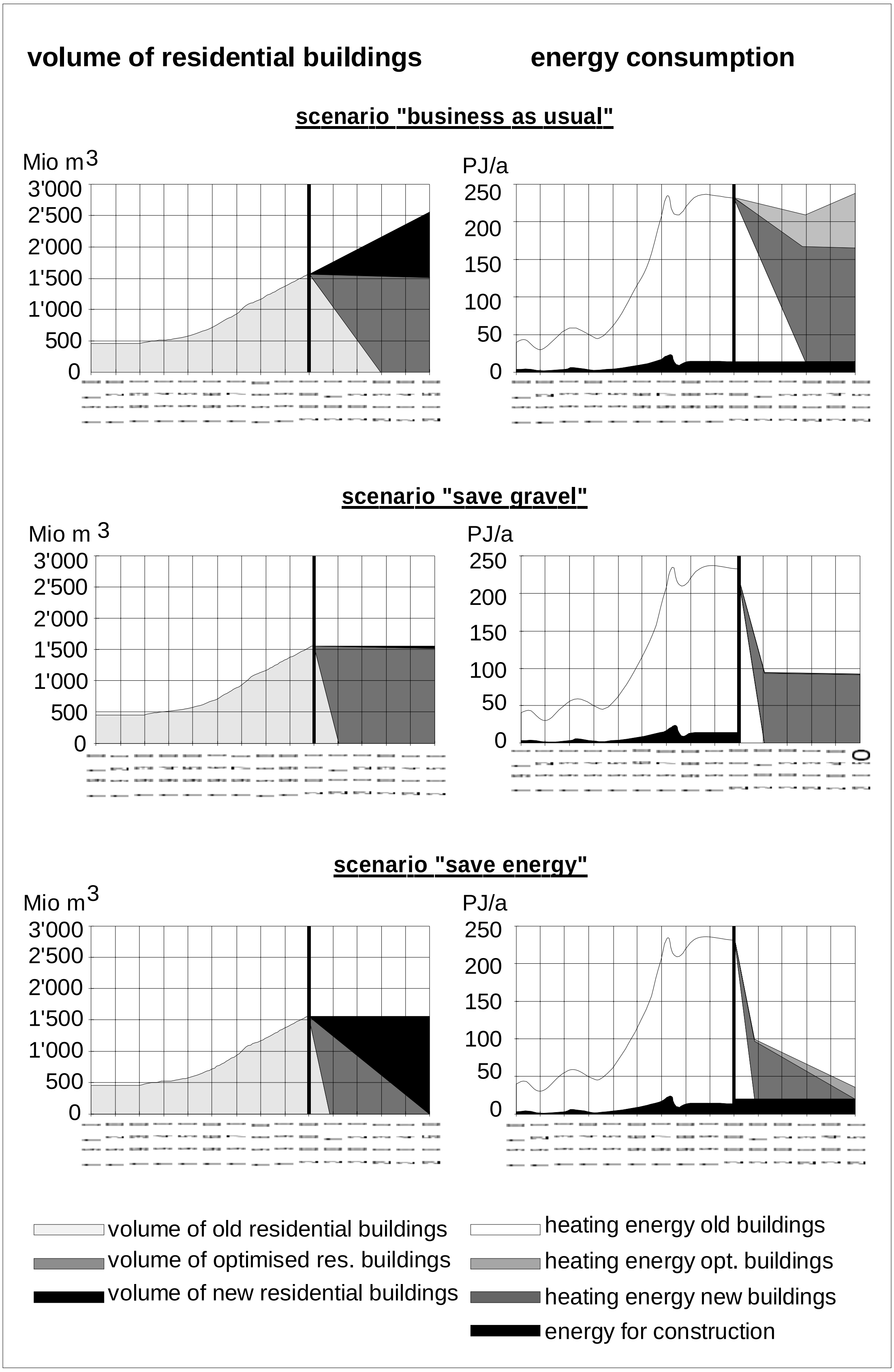

Fig. 11. Volume of residential buildings and energy consumption in the scenarios “business as usual”, “save gravel” and “save energy”.

3.2 Consequences for Implementation

How can a MFA encourage and support an environmental policy aiming at sustainable development ? In order to give a preliminary answer to this question, the following three aspects will be discussed:

– How can data from a MFA be converted into information (see 3.2.1) ?

– How can an environmentally-oriented analysis such as a MFA be combined with an evaluation of economic implications of possible measures (see 3.2.2) ?

– How has a MFA been applied so far, and what are the lessons learned from past experience (see 3.2.3) ?

3.2.1 From Data to Information

Most environmental information systems currently applied to support policy decisions focus either on the ecological aspects of an environmental problem only or analyse the impact by the anthroposphere. To combine these two aspects a common and consistent method to describe the ecological and anthropogenic systems and their interdependencies is required. Material Flow Analysis can be used for this purpose [Bader and Baccini 1997]:

– It can describe different elements of biological (e.g. growth of forests), hydrological (e.g. water transfer in soil and aquifer), economic (e.g. consumption or production of paper products) or other systems, and combine them in a material management model. System simulations can, thus, be established (see examples in 3.1.2 and 3.1.3). The results obtained go beyond assessing the status quo or describing possible trends. They reveal how a system functions and how it can be influenced by political action and what difficulties it may encounter (e.g. conflicting goals “energy vs gravel conservation”).

– With the help of a MFA approach, the focus can be put on the most promising political actions and evaluate these in scenario calculations (e.g. putting stress on building construction rather than paper consumption in a regional biomass management).

– MFA models can be combined with information necessary to evaluate the status quo or the results of political action (e.g. environmental assessment or cost/benefit analysis). An example is given in 3.2.2.

– The mathematical description of MFA models shows the type of data necessary to completely describe the system. One can, therefore, concentrate on measuring the essential data and estimate the “missing links” (see 2.2 and 2.3). In a material accounting system, this MFA modelling feature can be used to collect data efficiently.

– As data is collected from various sources (statistics, literature, interviews etc.), a MFA model has to be a tool for data integration. It is well-suited for this purpose. Since it gives a general description of the interactions between the various processes and their characteristics (see 2.1 and 2.3), data inconsistencies become apparent when estimating flows and stocks by means of this data.

3.2.2 Combined Environmental and Economic Evaluation

To evaluate environmental and economic aspects of the status quo or possible political actions, some kind of economic-ecological model is required. A MFA can form the basis for this model. The scenarios for construction material management presented in 3.1.3 are given as examples to illustrate how this can be achieved and the results thereby obtained.

The following three steps were used to develop an economic-ecological model based on a MFA:

a. *Introduction of economic actors, monetary stocks (assets) and flows (costs and benefits).* In the material management system for construction materials (in combination with energy) shown in Figure 5, two economic actors are introduced: *owners* and *tenants* of residential buildings. Owners are responsible for construction, maintenance, renovation, and demolition of *residential buildings.* Tenants are in charge of the buildings´ operation. Monetary stocks are introduced into the material management model by including the monetary value of residential buildings (described as monetary stock in the process *"owner"*). Monetary flows occur in combination with flows of material and energy (material and energy costs or turnover) or in combination with stocks (e.g. rents, interests, changes in value).

b. *Assessment of monetary stocks and flows with economic data* (using the same methodology as described in 2.2 and 2.3). It is assumed that monetary stocks and flows can be described in the same way as stocks and flows of material (e.g. changes in value of residential buildings are described as (positive or negative) flows into the process *"owner"*). To describe the status quo, data from statistics, literature or expert interviews is used.

c. *Defining a model specification to describe the reactions of the economic actors to changes in system parameters*. To illustrate the general idea, a very simple model specification is chosen: it is assumed that the change in value of residential buildings is dependent on annual rates of construction, renovation and demolition, specific rate changes in value for various types of buildings, and on the national rate of inflation. All other economic variables are dependent only on the building volume.

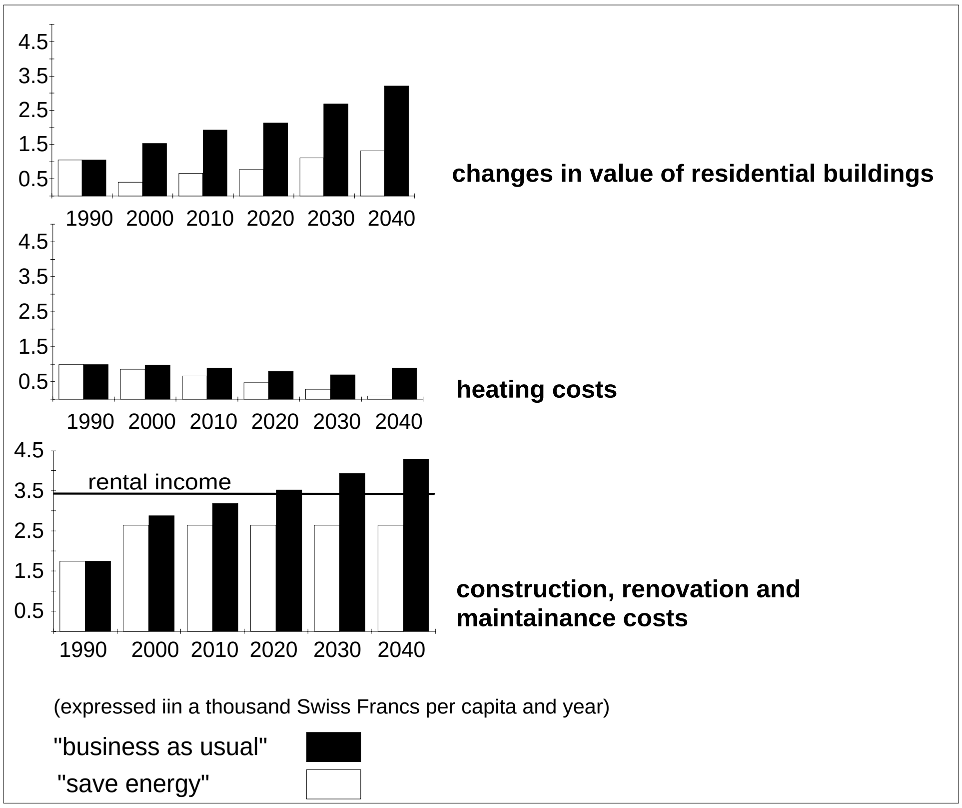

Fig. 12. Development of economic indicators in the scenarios "business as usual" and "save energy" (see 3.1.3) calculated on the basis of data for the city of Olten (reference year: 1990) and model assumptions.

The scenarios "business as usual" and "save energy", presented in 3.1.3, were calculated with this economic-ecological model. The results obtained (see Fig. 12) reveal that on a long-term basis the management strategy described in the "save energy" scenario is economically attractive for both *owners* and *tenants* as it reduces the maintenance and heating costs.

3.3.3 Lessons Learned from Past Experiences

In Switzerland Material or Substance Flow Analyses have been applied frequently as decision support tools in environmental policy since 1980. The following two cases have been chosen to analyse these experiences:

phosphate in detergents: In 1983 the Federal Commission for the prevention of water pollution established a working group that was engaged to evaluate technical, economic and environmental aspects of the use of phosphate in detergents. A Substance Flow Analysis for phosphate was elaborated in the evaluation process [BUS 1983] [Baccini 1985]. The results showed that a significant reduction of phosphate concentrations in Swiss lakes could be achieved with a combination of measures, including a ban of phosphate in detergents and a change in agricultural practice. The Federal Commission supported the working group's proposal to ban phosphate in detergents. This proposal was accepted by the parliament and became part of the federal regulation in 1985. The effort proved to be a successful strategy in the following years. But as phosphate emissions in municipal waste water were reduced significantly the phosphate emissions caused by agriculture became dominant [Siegrist and Boller 1996]. Since the early nineties the Swiss Federation has begun to change regulations and economic policies in order to enhance an agricultural practice with less effects on water quality.

federal and canton waste management policies: In Switzerland Material Flow Analysis has been used in waste management since the middle of the eighties. It was applied to support decisions on general and long-term oriented goals in waste management [Baccini et al. 1985] [BUS 1986] and to establish and enforce federal and canton regulations. Recently efforts are made to improve management strategies for construction waste. Environmental protection agencies in several cantons have applied Material Flow Analysis to estimate total amounts and compositions (qualities) of present and future construction waste [Baudepartement des Kantons Aargau 1995] [Baudirektion des Kantons Zürich 1996 and 1997]. The results have been the basis to establish waste management plans including a set of measures for waste reduction, waste treatment and recycling. Future efforts in construction materials management aim at providing sufficient capacity for waste treatment and improving information, education and motivation of planers, executives and construction workers. Furthermore, in some cantons (e.g. Zürich) Material Flows Analysis is established as a tool to evaluate the future development of the construction materials management system (controlling and forecasting) [AGW 1997].

The results of the analysis of these cases can be summarised as follows.

A. Benefits of MFA as a decision support tool

- MFA is used to evaluate environmental policy measures aiming at different economic processes that contribute to the same environmental problem (e.g. in the phosphate case). In a decision making process this allows for the discussion of a wide range of possible actions and the comparison of their benefits and shortcomings on the basis of a common system definition and a common set of data. During the process of a group decision the discussion can, thus, focus on valuation aspects and reveal individual and group preferences.

- MFA is used to forecast the effects of social and economic developments on materials management systems (e.g. in the construction waste case). This forecast is based on data on current material stocks, an analysis of the materials management system and assumptions on technological developments and human behaviour. In a decision making process it provides information about possible future "problem shifts" and can, therefore, be a basis for long term planning.

- If MFA is applied repeatedly for the same system it can reveal the success of measures which were taken in the past and support continuos efforts to fight an environmental problem (e.g. in the phosphate case). It can also keep a forecast on a materials management system up to date and enhance awareness for future problems (e.g. in the construction waste case).

B. Promoters and Obstacles

- Public awareness of the existence and importance of an environmental problem is a vital promoter for a MFA which provides the basic information to solve this specific problem. This awareness has so far not been created by the use of MFA itself but was a result of research on environmental qualities in general (e.g. in the phosphate and construction waste case). One reason for this shortcoming might be that MFA is still primarily used and discussed among scientists and experts.

- A limited scope of action is a major obstacle to a successful application of MFA in decision making processes. MFA results can reveal that processes which are crucial for a problem's solution can't be influenced directly by the decision makers. Decision makers can only try to influence these processes via information or education (e.g. in the construction waste case) or use the MFA results as basis of further discussions or decisions (e.g. in the phosphate case).

- MFA is applied to evaluate material management systems on different scales (e.g. municipal waste incineration, regional waste management, nation-wide waste policies). In some political fields it is therefore frequently used as a decision support tool and the general acceptance of results as well as the data quality improve continuously (e.g. in the phosphate and waste management case).

4 Conclusions

4.1 Use of Material Flux Analysis in Evaluating Sustainable Development in Resource Management

Material Flux Analysis (MFA), supported with mathematical models, is a liable tool to

- elucidate the potentials and limits of essential mass goods (water, biomass, construction materials and energy) with respect to their exploitation and their role as sinks for anthropogenic emissions,
- assess the anthropogenic stocks of essential mass goods,
- sketch long term scenario with regard to concrete goals of a regional development, such as "sustainability".
- use the elaborated regional material management systems to assess any specific material flux for which a minimum data set is available,
- link material management systems to economical systems and to gain additional information on the interdependence between material and money fluxes.

The necessary data to convey a MFA is available in all countries disposing of statistical records with regard to the main mass goods. The main challenges in applying the method are the set up of an appropriate material management system and the critical selection of basic data. These skills can only be gained by a well founded training on a sophisticated academic level.

4.2 Material Flux Analysis - a Tool in Political Processes and Decision Making

Experiences with MFA in political processes are still rare and have not yet been investigated deeply enough and on a broad level. The two cases presented lead to the following three hypothesises:

MFA in political processes can

- improve significantly the transparency of the scientific data applied to base the main arguments of the different actors in the political debate (finding a common platform with regard to the status quo)
- help to find a common language with respect to the topic in debate, by systematising and integrating information coming from very different disciplines
- improves the ability of the actors to participate in the finding of feasible scenario at an early stage and to visualise possible consequences of certain measures.

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