Systems analysis of stock buffering: development of a dynamic substance flow-stock model for the identification and estimation of future resource, waste streams and emissions

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Chapter 1 Introduction

1.1 Introduction

Over the last century, the increase in the global population and the growth of the economic activities have been accompanied by an increase in demand for materials, with a consequent increase in extracting, processing, using and waste treatment activities. These economic activities give rise to environmental problems. Some of these problems are related to the extraction of resources, others to emissions and waste flows resulting during the life cycle of these materials including energy resources.

A number of analytical tools have been developed to manage the environmental impact of extraction and emission related problems. These include Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Substance Flow Analysis (SFA) and physical Input / Output (I/O), which in different ways study the flows of substances, materials and products through the economic system and their impacts on the environment. Each of these tools has its own purpose and methodology (see Heijngs, 1997, van der Voet, 1996, Fisher-Kowalski, 1998). LCA is a tool for analysing the environmental burden of a product through all the stages in its life cycle, from the extraction of resources, through the production of materials, product parts, the product itself and its use, to its management after it is discarded, either by reuse, recycling, or final disposal (Guinee et al., 2001). MFA is an analytical tool that systematically describes material flows, generally for a region, expressed in physical units (kilograms, tons), through extraction, production, transformation, use, recycling, and final disposal as waste or emissions. MFA has been used to evaluate losses during the material life cycle and to provide measures for the more efficient use of resources (Bringezu, et al., 1997). MFA can be performed on different levels. It is performed to include the total material flows within the system, which is referred to as bulk MFA (Kleijn, 2001) or for specific materials such as biomass, or in a narrower sense for a chemical element or compound, which is referred to as SFA.

SFA is an analytical tool that is used to describe or analyze the flows of one or more substances into through and out of a system. It has been used to identify the direct, economic and ultimate causes of environmental problems (for example for Cadmium soil load, the direct cause is atmospheric deposition, which is caused by incineration. Its ultimate origin lies in the flow of zinc) and to identify the most effective policy measures to eliminate or to reduce them (van der Voet, 1996).
Within the framework of SFA, several types of analysis can be used. These include accounting and static and dynamic modelling. So far the attention in the SFA community has been focused mainly on drawing accounts and on comparative static modelling (Bringezu et al., 1997; Bauer et al., 1997; Anderberg et al., 1995). Recently it has been acknowledged that an important difference between static and dynamic models lies in the inclusion of stocks in society: substances accumulated in the stocks of materials and products in households or in the built environment (Bergbäck & Lohm, 1997; Fraanje & Verkuijlen, 1996). These stocks can be very large and, sooner or later these will lead to waste and emissions. The present stock of materials in society will strongly influence future waste streams and emissions of many hazardous substances to the environment.

Matthews et al. (2000) have shown that the growth of such stocks is not restricted to individual or isolated substances or materials, but overall is a significant phenomenon in society. The total societal stock (of materials) increases each year by approximately one third of the total yearly material inflow. Most of this goes into materials for building and other infrastructure. At some point in the future demolition waste streams can be expected to rise.
Other studies have shown a decline in point source emissions within most industrialized countries. However, future emissions from built-up stocks may be considerable. Bergbäck and Lohm (1997) and Guinée et al., (1999) have argued that emissions of heavy metals have decreased over the past decades, but at the expense of a stock increase. This includes not only the stock that is in use, but also materials that have been kept in storage or left underground. Bergbäck and Lohm (1997) concluded that such "hibernating stocks" might be very large. Kleijn and van der Voet (1998) pointed out that the future worldwide emissions of CFCs from present stocks would be in the same order of magnitude as accumulated past emissions, even assuming a complete phase-out of this chemical.

A crucial issue for environmental policy, therefore is to forecast future emissions in order to anticipate future problems and take timely action. However, models used for estimating future emissions and waste streams mostly ignore the stocks, due to a lack of data and insufficient insight in the dynamics of such stocks. In consequence they are completely left out of environmental forecasts.

Economic models are often used to estimate future emissions. They are used to explore future production and estimate future emissions by assigning emission factors to this production. For waste, a generally similar approach is used: the volume of waste streams is assumed to be directly related to economic development. While this approach has some value on a general level, it clearly leads to dubious outcomes when looking at emissions of specific substances and waste streams of specific materials. Economic models usually ignore some of the crucial mechanisms that underlie the generation of waste and emissions (van der Voet and Kleijn, 2000). They particularly ignore physical laws, such as mass balance and stock building over time. Such shortcomings in economic analysis have been discussed in several studies (Georgescu-Roegen 1973, Ayres, 1997, Heijungs, 1997). Another way to predict future emissions is to use material flow models. These models capture some aspects much better, but are limited to physical considerations and do not include costs or description of the mechanisms of economic analysis. These models have no rationale for predicting any future developments, other than applying mass balance. To obtain more accurate predictions, elements from both types of models should be combined. Recently several studies have pointed out the need to combine physical models with economic models (Boumann et al., 2000, Brunner, 2002 and Kytzia and Nathani, 2004) and some attempts have been made to integrate these two approaches (Ayres and Kneese, 1969, Leontief, 1970, Victor, 1972, Ruth, 1993 and Feber and Proops, 1997, Elshkaki et al., 2002).

This chapter provides an introduction to the thesis. The following section describes the aim and scope of the research presented in this thesis, section 3 contains the scientific background, section 4 discusses the main issues addressed in this thesis, section 5 describes the selected case studies and section 6 outlines the structure of this thesis.

1.2 Aim and scope

The first main aim of this thesis is to systematically gain insights into the mechanisms that determine the generation of future emissions and waste flows from present stocks due to both socio-economic and physical/chemical aspects. It seeks to find ways to integrate these insights into substance flow models that can explore future emissions and resource availability in a meaningful manner. It then employs this model, using stock dynamics and combining elements from both economic and physical models, to evaluate the effectiveness of different policy options.

As such, the research presented in this thesis follows three consecutive stages:

- The first part develops a dynamic stock model, which combines elements from both physical and economic models, in order to estimate current and future waste streams, emissions and resources, and establish a link to a flow model, thus creating a dynamic substance flow-stock model (chapter 3 of this thesis).

- The second part develops a software tool able to carry out such a model.

- The third part implements the model in two case studies relevant to environmental policy (chapters 4 to 8 of this thesis). The first case study investigates the environmental and economic consequences of the development of lead stocks in the EU (chapter 4) and The Netherlands (chapters 5 to 7). The second case study investigates the potential impacts of using platinum in the newly introduced Fuel Cell technology and addresses issues of both resource availability and environmental impacts (chapter 8).

1.3 Scientific background

Substance flow analysis (SFA) originates from natural and engineering sciences (van der Voet, 1996; Ayres, 1998) and falls within a relatively new scientific field of research: Industrial Ecology. Industrial

Ecology, also called the science of sustainability, is formulated in a way that is analogous with ecology. It is concerned with studying society's metabolism to analyze the causes of environmental problems and indicate possibilities for more sustainable management of materials (Graedel and Allenby, 1995).

SFA considers the physical dimension of the economy as described in the concept of industrial metabolism (Ayres, 1989). This term is defined as the set of physical and chemical transformations that convert raw materials (biomass fuels, minerals, metals) into manufactured products and structures ("goods") and wastes (Ayres and Simonis, 1994). SFA focuses on the industrial metabolism of substances. It determines their main entrance routes to the system, transformation or storage within the system and output from the system.

SFA is one of the main analytical tools within the research field of industrial ecology, which is largely driven by engineering approaches and systems perspectives (Ruth, 2006). It is used to describe or analayze the flows of one substance or group of substances in, through and out of a system (van der Voet, 1996). SFA considers physical entities, often a geographical area, and is divided into two subsystems: the economic or societal and the environmental. Systems analysis is the science dealing with complex systems and interactions within those systems. It does so by applying mathematical methodologies to form an overall picture of the systems. Two types of system analysis methods can be distinguished; hard and soft systems analysis (Checkland, 1981). Hard system analysis is a scientific approach for problem solving, which deals with well-defined problems and which aims to provide an ideal and unambiguous solution. Soft system analysis is a qualitative technique, which deals with poorly defined problems with a possibility of different interpretations. Its outcome is more generally improved understanding, rather than a specific solution. SFA is a hard system analysis approach.

The system flows and stocks in SFA are quantified either by accounting or by modelling (substance flow accounts, static SFA models, and dynamic SFA models). The dynamic SFA model includes stocks in society, and combines physical, socio-economic and engineering elements. Stocks of products and materials in use represent a major reservoir of materials that cause a disconnection between the inflows and outflows through the economic subsystem in any one year. This is because substances, locked into applications with a long life span, such as building materials or durable user goods, have a long residence time in society. The dynamics of the growth and decline of the stocks of any substance over time are determined by the inflow and outflow of materials and products that contain it. The inflow is determined by the demand for the products containing those materials and substances, and can be derived from socio-economic information. The outflow is mainly determined by two physical mechanisms, those of leaching and delay. The delayed outflow is based on residence time theory, well-established theory in chemical engineering (Melo, 1999).

The results of SFA are interpreted by transforming the overview of the system flows and stocks into policy relevant information that uses specific indicators (Van der Voet, 1999, 2000) and/or Life Cycle Analysis (LCA) impact categories (Tukker, 1996; Udo de Haes et al., 1999), which are based on environmental science. SFA can further be used as input for further analysis mainly risk assessment.

1.4 Issues addressed in the thesis

Resource availability and environmental quality start to become serious problems when the extraction of resources, the emissions of hazardous substances and the disposal of waste occur at rates that exceed the capacity of the natural system (Braat and Lierop, 1987). Issues and concepts related to the world's finite resources and limits for expansion, the principals of the conservation of mass and the constrains imposed by the first and second laws of thermodynamic on the effective use of resources have been widely discussed (Meadows et al., 1972, Rothmans, 1990, Alcamo et al., 1993, Ayres, 1999, Tilton, 1999, and Tilton, 1996).

In this thesis, the main issues discussed relate to the availability of resources, especially those required for new technologies that aim to increase sustainability, the emission of hazardous substances and to waste flows.

1.4.1 Resource problems

Resource problems, which can occur with both renewable resources (such as fish, timber and topsoil), or non-renewable ones (such as minerals and fuels) occur when there is shortage of supply of resources required for production and consumption.

The depletion of resources was predicted several decades ago by the Club of Rome in their publication "Limits to Growth" (Meadows et al., 1972), which was based on a system dynamic model. Since the publication of their report, interest in the issue of resource depletion has declined somewhat, particularly over the availability of ores. This is mainly due to the observation that the world is not running out of mineral resources, as the profitable extractable reserves of many commodities has in fact increased. Recent concern about the depletion of resources has shifted towards the question of the depletion of renewable resources, such as rainforests and fish stocks. However, the discussion about the availability of mineral resources is still ongoing. Tilton (1996) points out that the debate not only continues but has become even more polarized with two schools holding two different views. The first school, often made up of ecologists and engineers, is concerned about the limitations of the earth in supporting current and anticipated demand for exhaustible resources. The second school, often composed of economists, claims that with the help of market incentives, public policies and new technology the earth can meet society's needs for an indefinite future.

The latter group cite evidence that cost reductions due to the new technology will make more resources available and that these will exceed cost increases caused by the depletion of cheaper deposits (Reynolds, 1999). Equally, before resources are exhausted, demand will decline due to rises in the cost, simultaneously stimulating the development of alternatives and increasing the stock (Hotelling, 1931). The first school argues that increases in profitable extractable reserves are due to the availability of cheap energy sources from fossil fuels that are being rapidly depleted (Richards, 2006) and whose use creates serious and long-term environmental impacts. This shift in the problem was predicted by the authors of the limits to growth when they revisited the issue in their subsequent book "Beyond the Limits" (Meadows et al., 1992), in which they predicted a collapse of modern civilization due to the environmental damage caused by the over-production and over-consumption of resources.

1.4.2 Emissions and waste problems

Emissions and disposal of waste and by-products from economic activities and the associated energy used in these activities can give rise to changes in environment quality. These problems involve both macro and micro-pollutants. Problems related to macro-pollutants include the overload of specific substances in specific environmental mediums. Examples include, global warming which is caused by the increase in the stock of CO_2 in the atmosphere and eutrophication, which is caused by the increase of nutrient stocks in lakes and shallow coastal waters. Problems related to micro-pollutants include the emission of certain noxious substances, even in small quantities, which disturb natural processes and threaten the health of humans and ecosystems due to their toxicity, carcinogenity, mutagenicity or hormone mimicking properties. Examples include persistent organic micro-pollutants and heavy metals, both of which are generally emitted in small quantities but accumulate in the environment because of their non-degradability (Van der Voet et al., 2000).

Several measures can be taken to address these problems. These include end-of-pipe technologies, increasing recycling and phasing out hazardous intended or non-intended applications. Some argue that advances in technology can provide a solution to most of these problems. For example several remedial technologies (physical, chemical and biological) have been introduced to address problems of emissions and waste. It is argued that physical treatment technologies, such as landfill or dilution and dispersal through smokestacks do not provide effective solutions due to the limits imposed by the principals of the conservation of mass. Thus these technologies transfer risk from one place to another or from the present to the future. Chemical and biological treatment technologies, while often more effective than physical technologies, can also have undesirable side-effects (Huesemann, 2001).

Recently industrial ecologists have been reinforcing and underpinning earlier arguments about the possibility of preventing environmental pollution by redesigning industrial processes (i.e. industrial processes with zero emissions) and closing the material cycle (Ayres and Simonis, 1994: Graedel and Allenby, 1995). While it is possible to substantially reduce emissions, it is not possible to achieve 100% recycling and zero environmental impacts. Industrial processes with zero emissions require significant amounts of energy, which has negative impacts. Moreover, in thermodynamic terms 100% recycling is an impossibility (Huesemann, 2001).

1.4.3 Co-production problems

Co-production problems relate to the issues, discussed above, of pollution and resources. In some cases and in the short term, measures aimed at phasing out the use of some substances in some applications appears to be effective. In the longer term however, their effectiveness is questionable, especially in instances involving the co-production of substances. Well-known examples are cadmium recycling (Huppes et al. 1992) and mercury recycling (Maxson et al., 1991) (see below). Since these substances are co-produced with other materials, increases in demand for the other materials might well lead to an increase in their emissions.

Co-production occurs when the same processes or system produces two or more products. Co-production of products is considered a problem in system modelling within LCA and is normally solved by the technique of co-product allocation (Weidema and Norris, 2002). In terms of substances, co-production is the production of two or more substances from the same process due to the natural existence of substances in the same deposits. In nature, substances exist in the same deposit with different concentration and quantities. Substances with high concentration and large quantities are referred to as host materials and those with low concentration and small quantities are refereed to as rare or less abundant materials. The problems of co-production might result from the demand for the host materials or from the demand for rare materials.

Examples of the co-production problems due to the demand for the host materials are those related to the recycling of cadmium and mercury. Cadmium enters the economy as a pollutant in zinc. On the short term, recycling may reduce cadmium emissions, however, on the long term these emissions might increase due to the fact that the inflow of cadmium into the economy is supply driven (i.e. the demand for zinc will increase the supply of zinc and hence of cadmium) (Huppes et al. 1992). This implies that a reduced demand for cadmium does not result in a reduced supply. A comparable example concerns mercury. The demand for mercury has decreased so much as a result of a strict policy that its supply can be covered completely from by-product sources, such as from the purification of natural gas. An increase in the demand for natural gas will lead to an increase in the supply of mercury. In this case, policies aimed at phasing out or recycling mercury applications therefore might increase its stock in society and consequently an increase in the future emissions (Maxson et al. 1991).

Examples of co-production problems due to the demand for rare metals are those related to the availability of platinum, indium and bismuth. These materials are mostly co-produced with other more abundant materials. Bismuth is mainly found in the same ores with lead, platinum is found with nickel and copper and indium is mainly found with zinc. Some of these rare metals are used in new technologies such as the use of platinum in fuel cell technology or the use of indium in solar cell technology. Others are used to substitute other materials in existing technology such as the substitute of lead by bismuth. For a more widespread use of these technologies, the production of these rare metals must be expanded, especially in the short and medium term when the recyclable stocks in the economy are still being built up. Since their production is linked to that of their "host" materials, this ultimately implies an increased production of these host metals (Zn, Pb, Cu or Ni). Consequently an increased supply of the jointly produced Zn, Pb, Cu or Ni may well have environmental consequences; the more so as lower prices of the host materials will make extraction of the metals from wastes for recycling (here covering all manners of secondary use, including non-intentional secondary applications) less attractive

1.5 Case studies

The model presented in this thesis has been applied to two case studies related to heavy metals. Heavy metals cause problems to humans and ecosystems, due to their toxic properties and characteristics. Some of these metals are essential elements however when present in excess, they may create problems of toxicity. Others are not essential and may give rise to toxic manifestations even in small doses (Moolenaar, 1998).

Heavy metals have unique chemical and physical properties, which made them attractive for many industrial applications. Due to their extensive use in the past, especially in applications with long life spans, large stocks of these metals have been built up in the economy. Moreover, they continue to accumulate in the environment due to their non-degradability. Once they have entered the environment they remain there for a long time (Van der Voet et al., 2000). In addition to the direct (intentional) routes, heavy metals can also find their way into the environment, through indirect routes due to for example their presence as contaminants in other resources.

1.5.1 The consequences of the development of lead stocks

The first case study deals with lead, which was selected for several reasons. Lead is one of the most extensively used heavy metals in economic processes and consequently, large stocks of lead have been built up in the economy. Environmental concentrations may still be rising due to continuing emissions. Lead also has very toxic characteristics (Scoullos et al. 2001). It is cited by the American Environmental Protection Agency as one of the top 17 chemicals that poses the greatest threat to human beings and the environment (Wu et al., 2004). Lead can cause behavioural problems, learning disabilities, and even death especially among children who inhale or ingest it. In addition lead can be toxic to plants if presents at high concentration, diminishing their productivity or biomass, and eliminating some species (Singh et al., 1997, Xiong, 1997, and Patra et al., 2004).

In the Netherlands there is a policy of reducing lead emissions by phasing out certain lead applications and increasing recycling. The applications from which lead has been phased out include water pipes, paint and gasoline. Since July 2006 an EU directive prevents member states from allowing new electrical and electronic equipments containing lead, mercury, cadmium, chromium VI, and PBB or PBDE to be put on the market (European Commission, 2006). In the short term, the phasing-out policy has resulted in a reduction of lead emissions (Tukker et al. 2001) and recycling has led to less waste containing lead going to landfill. In the long term, however, both measures may have unexpected and undesirable side effects such as an oversupply of lead and a consequent increase in the landfill and incineration streams at the expense of recycling, which may ultimately lead to an increase in emissions. It is argued that for long-term management, more information is required on the dynamic behaviour of substances in the economy (Guinée et al. 1999).

The case study aims to assess the effectiveness of certain policy options and to highlight certain mechanisms that those designing policy need to be aware of. For example, a ban on all applications of a certain heavy metal – the most drastic policy option available – could lead to an environmental problem. These issues are discussed in chapter 5 of this thesis.

In addition to its intentional use, lead is also present in several economic applications, due to its natural occurrence in fossil fuels, other metal and phosphate ores and through secondary flows resulting from the processing of waste flows of its intentional applications. Lead may threat human health through indirect routes of non-intentional flows. For example, lead enters the agricultural chain via phosphate fertilizer and accumulates there, leading to significant concentrations in manure. Processing metal ores and the use of fossil fuels leads to emissions of lead to the environment. Both intentional and non-intentional applications of lead may end up in waste streams. Part of this waste is landfilled, and part is used as fly ash, bottom ash and slag in construction materials. In addition to direct emissions of lead to the air, water and soil, the accumulated lead in roads, buildings, agricultural soil and landfill sites may leach to the soil or ground water.

This case study also aims to evaluate the long-term environmental and economic consequences of the non-intentional flows and stocks of lead and to compare the consequences of these non-intentional flows with those of its intentional flows. An important issue in this case is the one related to resources. The availability of lead in utilized and landfilled secondary materials (fly ash, bottom ash and slag) generated from the production of other heavy metals, electricity production from coal and the incineration of intentional applications of lead provide potential secondary resources for lead. These issues are discussed in chapters 6 and 7 of this thesis.

1.5.2 The impacts of using platinum in the newly introduced Fuel Cell technology

The second case study deals with technologies intended to promote sustainable development. Several new technologies that offer the potential for a transition to a sustainable society require the use of rare often co-produced metals. In the short term, each of these technologies may serve its intended purpose. In the long term, however, there may be side effects that will ultimately limit their combined and wider application. This includes potential bottlenecks in the supply of specific materials and the possible hazards posed by new emissions.

Recent studies have shown that the availability of rare metals may be a real bottleneck in the broad implementation of some new promising technologies (Anderson, 2001 and Graedel, 2002). These metals include indium and germanium (used in solar cell technologies), bismuth and germanium, used in lead-free electronic solder, and some precious metals, i.e. platinum and palladium, used in car catalysts and fuel cells. Active investigation may lead to these limits being overcome, through substitution or through increased availability based on adjoining technological development in primary and secondary production.

This case study aims to systematically determine the resource limitations and emissions problems that the increased use of rare metals in new technologies may give rise to. It does so not for individual technologies, but for a bundle of several such technologies. It also investigates how such resource shortages might be avoided.

These materials are mostly co-produced with other, more abundant, materials such as lead, zinc and nickel. For a more widespread use of these new technologies, production of these rare materials must be expanded, especially in the short and medium term while the recyclable stocks within the economy are being built up. Since their production is linked to that of their "host" materials, this ultimately implies an increased production of these more abundant heavy metals such as Zn, Pb or Ni. This increased supply may well have environmental consequences, the more so as lower prices will make extraction of these metals from wastes for recycling (covering all manners of secondary use, including non-intentional secondary applications) less attractive.

To date the potential impacts of increased demand for co-produced rare metals on the cycles of other metals has not been adequately investigated, either in terms of resource depletion or in the terms of final waste generation and emissions. This case study aims to fill this gap and assess how the potential side effects on the material cycles of the host metals could be limited at an early stage of the technology development. These issues are discussed in chapter 8 of this thesis.

1.6 Content of the thesis

This thesis consists of 9 chapters. Chapters 2 and 3 are dedicated to methodological aspects of substance flow analysis (SFA) and a representation of the dynamic flow-stock model. Chapter 2 includes a general background on substance flow analysis methodology, related modelling aspects and computer tools used in modelling SFA. Chapter 3 describes the substance flow-stock model, the main elements within the system, the relation between flows and stocks and between flows themselves. It quantifies and evaluates these relations, and the factors affecting the dynamic behaviour in the system.
Chapters 4 to 8 include applications of the model in case studies and are based on papers published or submitted to international scientific journals and a chapter in a book. The first case study, concerning the environmental and economic consequences of the development of lead stock-in-use in the EU and Dutch

economic systems, is presented in chapters 4 to 7. Chapter 4 concerns the development of lead stocks in use in the EU. Chapters 5 to 7 explore the same theme in the Dutch context. Chapter 5 describes the modelling aspects, presents the data, and analyzes the long-term management of the intentional use of lead. Chapters 6 and 7 describe the long-term development of the main sources of the non-intentional flows and stocks of lead, evaluate their environmental and economic consequences and compare the consequences of these non-intentional flows to those of intentional flows. The second case study, which concerns the impact of using platinum in the newly developed fuel cell technology in terms of supply constrains and other emissions problems, is presented in chapter 8. Chapter 9 is dedicated to a general discussion, conclusions and recommendations of aspects related to the substance flow-stock model and its applications.

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