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 4 Dynamic Stock Modelling: A Method for the Identification and Estimation of Future Waste Streams and Emissions Based on Past Production and Product Stock Characteristics [*]

Abstract

Large quantities of products, materials and substances have accumulated in society. This chapter investigates the dynamic behaviour of these societal reservoirs or stocks in order to explore future emissions and waste streams. We argue that the stock dynamics are mainly determined by its inflow and outflow characteristics. The stock's inflow is determined by socio-economic factors, which can be quantified using regression analysis. Two processes determine the stock's outflow: leaching and delay. Leaching occurs during use and can be modelled as a function of the stock's size. Delay is related to the discarding of products after use and can be modelled as a delayed inflow distributed over time. This approach is illustrated by the case of lead as applied in cathode ray tubes in the European Union (EU). By applying this model to other lead applications and combining the results, the dynamic behaviour of the total lead stock in society can be described.

[*] Reprinted from "Elshkaki, A., Van der Voet, E., Van Holderbeke, M., and Timmermans, V. (2005). Energy; 30, 8, 1353-1363".

4.1 Introduction

Extraction, use and discarding of materials causes environmental problems. Some of these problems are related to resource depletion, others to pollution resulting from emissions during the life cycle of these materials. A relatively new field of research, industrial ecology, studies society's metabolism to analyse the causes of these problems and indicate possibilities for a more sustainable management of materials. Substance flow analysis (SFA) is one of the main analytical tools within the industrial ecology research field. SFA is used to describe or analyse the flows of one substance (group) in, out and through a system (Van de Voet, 1996). The system is a physical entity, often representing a geographical area. In most cases, the SFA system is divided into two subsystems: the economic or societal subsystem and the environmental subsystem.
SFA is based on the materials balance principle, which enables different types of analysis. Substance flow accounts can be used to identify major flows and accumulations and, if available for several years, to spot trends. Static SFA models can be used to identify the causes of pollution problems and to assess the effectiveness of measures (Udo de Haes et al. 1997). The main difference between static and dynamic models in SFA lies in the inclusion of stocks in society (Bergback and Lohm, 1997). Stocks of products and materials in use are a major cause of disconnection between the system's inflow and its outflow in one year. Ignoring them may lead to erratic forecasts of future emissions and waste streams. Dynamic SFA models including stocks lead to more accurate prediction of future resource use and waste streams. Considering stocks so far has resulted in a few specific substance stock inventories or models (Boelens and Olsthoorn 1998 and Kleijn and Van der Voet, 1998). This chapter contains an effort to define a general stock model. The dynamics that determine the growth and decline of the stocks of a substance over time are determined by the inflow and outflow of the materials and products that contain it. This chapter will focus on the inflow, which in turn is determined by the demand for the products containing those materials and substances.
Over the last century, the increase of the global population and the GDP per head in developed countries has been accompanied by a rapid increase in material consumption (Bergback and Lohm, 1997). In fact, the overall level of national income, the product composition of income and material composition of product have been used in determining the intensity of use of materials in several studies (Tilton, 1990 and Moor and Tilton, 1996). In this chapter, a likewise approach is adapted to estimate the stock's inflow. The modelling of the stock's outflow is mainly based on physical consideration, especially mass balance.
The next section will outline a methodology for dynamic stock modelling, followed by a description of the cathode ray tube system, and finally a section containing a discussion of the results and some conclusions.

4.2 Dynamic stock modelling approach

In the use phase, goods with a life span of more than one year tend to accumulate: they do not flow out again in the same year but remain stored for some time as products-in-use. Such applications stored in the use phase are referred to as stocks. The mechanism determining the stock dynamics can be classified into three levels:

- stocks of products, handled by producers and users (e.g. cathode ray tubes)
- stocks of materials that those products are composed of (e.g. lead oxide) and
- stocks of substances, contained within these materials and hence products (e.g. lead).

Stocks on these three levels have their own characteristics and dynamic behaviour.

The demand for a particular product is determined by significant variables such as its price compared to the price of the closest substitute, and the level of overall economic activities (Tilton, 1990). Moreover, in the course of time technological developments may also affect the demand for a particular product because of the emergence of alternatives. It may also affect the demand for materials due to changes in product design. For example, the developments in lead-acid battery technology led to a reduction of the total weight of a battery from about 19 kg to 16.6 kg over a period of 15 year. Most of the reduction of about 2.5 kg was obtained through reducing the lead content of the battery (ILZSG, 1999).
The dynamic behaviour of the product stock, which is mainly determined by the behaviour of the stock's inflow (purchases of new products) and stock's outflow (discarding of obsolete products) will be described in the following sections.

4.2.1 Modelling the product stock inflow

The total inflow into a particular stock of products-in-use is determined by supply and demand, each of these in turn determined by several further variables. Among these are socio-economic variables such as GDP, population, technological developments and welfare, as well as other economic factors such as the presence of alternatives and their relative prices. It is useful to start by making a qualitative model of the system. For example, it must be established whether or not there are any substitutes for the product, and if so, what their specifications are regarding material composition, performance and price. It is also relevant to know whether or not the product at present is subject to rapid change due to technological improvements, and if so, in which direction.
The second step is to quantify the relationship between the inflow of the product and the most influential variables (e.g. population, GDP). Time series data are required for the inflow on the one hand, and the explanatory variables on the other hand.
To establish the relative importance of these variables on the shape of the inflow curve over time, a regression model can be used. Regression analysis indicates the variables that are significant and contribute most to the shape of the inflow curve. It also examines the combined effect of significant variables.
The linear regression model used in this analysis is described by Eq. (1):

$$Y(t) = \beta_0 + \beta_1 \cdot X_1(t) + \beta_2 \cdot X_2(t) + \beta_3 \cdot X_3(t) + \beta_4 \cdot X_4(t) + \beta_5 \cdot X_5(t) + \varepsilon(t) \qquad (1)$$

where Y is the inflow of a particular good, the variables X_1, X_2, X_3, X_4, and X_5 are indicating the different influential variables, the parameters β_0, β_1, β_2, β_3, β_4, and β_5 are the regression parameters and ε is the model error

The adequacy of the regression model and the significance of the variables can be described in statistical terms such as the adjusted coefficient of determinations (R^2_{adj}), t tests and F statistics.
The derived regression model described by Eq. (1) can further be used to estimate the future inflow of goods. Projected values of the influential variables are then required. Such projections are available for GDP and population in different scenario studies (RIVM, 2001).

4.2.2 Modelling the product stock outflow

The outflow out of the stocks depends on the mechanisms of delay and leaching. Delay represents the discarding of products and is determined by the life span of the products. Empirical data on the life span is often not available (Kleijn et al. 2000). Either an average life span or a certain life span distribution can be assumed. Possible types of distribution are normal, Weibull, or beta distributions. In this study, the Weibull distribution has been used since it has been shown experimentally that Weibull distribution provides a good fit to the life span of many types of products (Melo, 1999). The outflow from the societal stock due to discarding is given by Eq. (2):

$$F^{out}(t) = F^{in}(t - L) \qquad (2)$$

where $F^{out}(t)$ is the outflow of goods at time t, F^{in} is the inflow of goods, and L is the life span.

Leaching refers to the emissions of the substance from the products during the use process. The emissions during use can be described as a fraction of the stock. For different applications, an emission rate can be established. For heavy metals for example, there are studies aimed at establishing a leaching coefficient describing the corrosion from surfaces exposed to the environment (Bentum, 1996). The outflow during use is given by Eq. (3).

$$F^{out}(t) = C \cdot S(t) \qquad (3)$$

where S is the size of the stock at time t and C is the leaching factor.

Reuse of products indirectly influences the stock's inflow as well as outflow. Reuse can be affected by several factors. Among these are technical and economic factors, which determine mainly the collection rate, and environmental policy aspects. When reuse must be modelled, these factors should be accounted for. In this model, the flow of waste products destined for reuse is modelled as a fraction of the total outflow by discarding as given by Eq. (4). On the material and substance level, recycling also plays a role.

$$R(t) = \alpha \cdot F^{out}(t) \tag{4}$$

where *R(t)* is the amount to be reused at time t, α is the reuse rate and $F^{out}(t)$ is the outflow of discarded goods as calculated by Eq. (2).

4.2.3 Modelling the product stock size

The change of the magnitude of the stock over time is the difference between the inflow and the outflow as given by Eq. (5).

$$\frac{dS}{dt} = F^{in}(t) - F^{out}(t) \tag{5}$$

By knowing the initial value of the stock and the inflow of goods, it is possible to calculate the stock as given by Eq. (6) and the future outflow using Eqs. (2) and (3).

$$S(t+1) = S(t) + F^{in}(t) - F^{out}(t) \tag{6}$$

4.3 Case study – Lead in cathode ray tubes

Lead was one of the first metals used by humankind, and its use has been extensive throughout history. Its unique properties such as its corrosion resistance, high density and low melting point make it suitable for several applications. A considerable use of lead is its application as a compound in cathode ray tubes (CRTs). A CRT is one of the components of television and computer monitors. Lead is used in CRTs as a protection from harmful radiation. The average weight of one CRT is 13 kg, of which 2 kg is taken up by lead. Figure 1 shows the CRT life cycle. The stock of CRTs is a part of this life cycle: it is accumulated in the "use" phase.

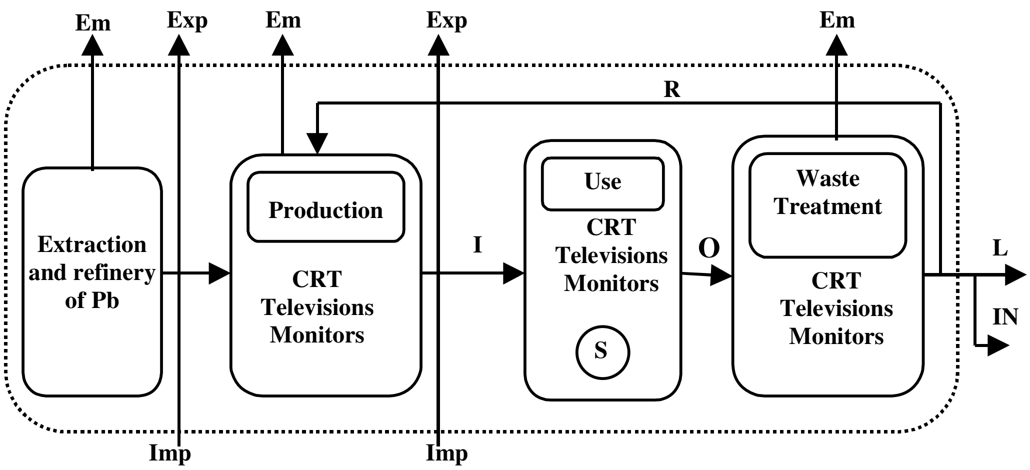

Fig. 1: The CRT life cycle: inflows and outflows of lead.

EM, emissions, I, inflow of goods into the stock, O, outflow or discarded goods, R, recycled stream, L, landfilled stream, IN, incinerated stream, S, stock of CRT, Imp, import, Exp, export.

4.3.1 The inflow of CRT into the societal stock

The inflow of CRTs into the product stock is calculated as the number of CRTs produced within the EU member states, plus the number of CRTs imported from outside the EU, minus the number of CRTs exported to non-EU countries. The inflow of CRTs is shown in Fig. 2 (CBS, 2000) and is expressed in terms of the lead it contains: in ktonnes of Pb. To model the inflow, we assume that the inflow of these products is affected by the availability of a viable substitute, by GDP, and by the size of the population.

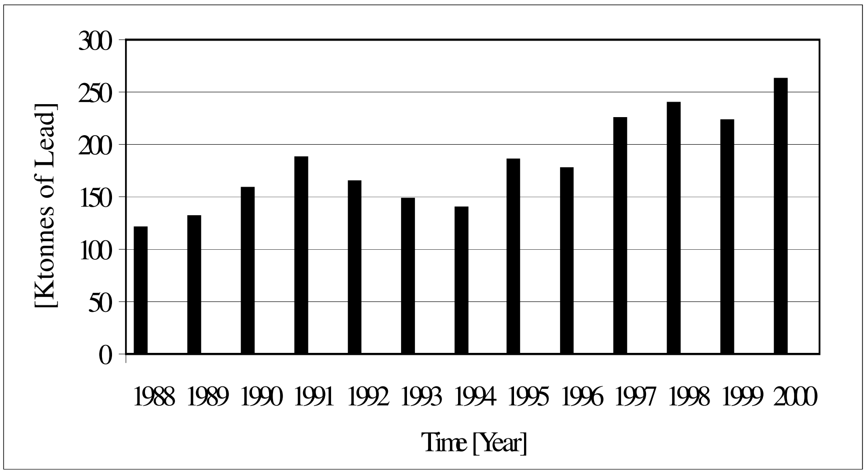

Fig. 2: The inflow of CRT into the stock–in–use in the EU expressed in ktonnes of Pb.

Gross Domestic Product (GDP)

Gross Domestic Product (GDP) is a standard measure in monetary terms of economic production and, mirrored, income. Other variables, such as poverty and natural resources exploitation are intimately connected to it, either positively or negatively. On a general level, the correlation between GDP and production and consumption of products is valid by definition. For specific products such as CRT, televisions and computer monitors this relation can be more complex, as some products tend to be used less with higher incomes and others more.

Population

There are several reasons to consider population a determinant of the use of products. In the first place, there is the general law that it takes more to sustain more people. This refers mainly to the basic needs. Nowadays, televisions and computers are transferring from luxury goods to basic items and therefore a correlation between the population and the consumption of these goods can be expected.

Substitution

In the present CRT system, there seems to be no viable alternative for lead. There are some indications that lead could be replaced with other materials such as barium, strontium and zirconium, but no such glass is commercially available and it is not known if these materials can be supplied in sufficient quantities to meet the demand. It is likely that the use of cathode ray tubes will decline as a result of the rise of flat screen displays. When forecasting future inflows, this development can be included under various scenario assumptions.

4.3.2 The outflow of CRT from the societal stock

Since no emission of lead occurs during the use of CRT, the outflow of CRTs out of the stock is determined only by discarding: it equals the amount of the discarded CRT, including those in discarded TV's and PC monitors. The most important leakage to the environment probably will take place after the disposal stage in waste management and/including recycling. The average life time of CRTs is about 15 years (Tukker et al. 2001). At the moment, the stream of final CRT waste is split between landfill (80%) and incineration (20%) (Tukker et al. 2001). For electrical and electronic equipment, however, the future recycling rates are predicted to increase. Leaded glass could be returned to glass manufacturers for recycling. At present, the glass industry is not doing this because there is no economic incentive to do so (Tukker et al. 2001). It is likely that the proposed EU Directive on Waste Electrical and Electronic Equipment (WEEE) will change this situation.

4.4 Empirical analysis and results

In this section, a preliminary empirical analysis of the CRTs inflow, outflow, stock and waste stream in the EU economy will be modelled and the model outcome will be discussed.

4.4.1 Modelling the inflow of the CRTs into the societal stock

To assess the relative importance of the explanatory variables for the CRT inflow, regression analysis is used. The independent variables used in the analysis are Gross Domestic Product (GDP), Population (Pop), and a Time variable (T) that will be used as a proxy for the combined influence of other variables on the inflow trend. The period of analysis was from 1988 to 1999. The fitting algorithm that determines the regression parameters (β_0, β_1, β_2, β_3) in Eq. (7) uses the ordinary least square (OLS) criterion (Gijbels and Rousson, 2001).

$$Y(t) = \beta_0 + \beta_1 \cdot GDP(t) + \beta_2 \cdot Pop(t) + \beta_3 \cdot T(t) + \varepsilon(t) \tag{7}$$

where *Y(t)* is the inflow of goods at time t, β_0 is the overall mean response or regression intercept, β_1, β_2, β_3 are the regression parameter or the main effect of the factors GDP, Pop, and T and $\varepsilon(t)$ is the regression model error term

Table 1 shows the result of the regression analysis. Estimations 1 and 2 show a positive correlation between the GDP and population variables and the inflow, with a fairly high coefficient of determination (R^2_{adj}). Estimation 3 shows a positive correlation between the inflow of CRTs and T. The correlation between the inflow of CRTs and all of the three variables separately is significant at the 95% probability level. The results indicate that the factors included in T (technological developments and substitution and maybe others) are important factors in the determination of the inflow shape, and therefore should be investigated further. The results show also that the coefficient β_3 has a positive value which means the inflow will increase over time. This indicates that in the past, substitution has not had any influence on the inflow shape. In the future, this may be different. It is clear from the estimations 4, 5 and 6 that the combination between the variables is improving the overall correlation. When all the three variables are included in the regression model (estimation 7), R^2_{adj} has the highest value. The t test for the individual coefficients shows that in this model the GDP and population are not significant. The coefficient for population has an unexpected negative sign, though this coefficient is statistically insignificant. However, the F test indicates that all the independent variables taken together are significant and contribute to the shape of the inflow. Therefore, the following model will be used to calculate the inflow of the CRTs:

$$Inflow(t) = 9225 + 0.015GDP(t) - 25.42Pop(t) + 37.1T(t) \tag{8}$$

Figure 3 shows the difference between the measured inflow of CRTs and the calculated inflow from the regression model in Eq. (8).

4.4.2 Modelling the outflow of CRTs from the societal stock

The outflow out of the CRT stock is the discarded CRTs, TVs and monitors. This flow is mainly determined by the life span of the CRTs in these applications. The life span is assumed to be distributed in time; a Weibull distribution is used assuming a minimum life span of 10 years and a maximum of 25 years, with a most likely life span of 15 years. The outflow is included in Fig. 4.

Table 1: Results of the analysis of the individual factors on the inflow of CRT

Estimation	Variables	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	β_3 (t-value)	R^2adj	F statistics
1	GDP	47.4 (1.10)	0.01 (3.18)			0.43	10.15
2	Pop	2521 (-4.52)		7.3 (4.84)		0.65	23.49
3	T	111.76 (8.49)			9.97 (6.01)	0.74	36.23
4	GDP, Pop	-3351 (-2.64)	-0.008 (-0.73)	9.7 (2.67)		0.63	11.51
5	GDP,T	133.5 (3.51)	-0.004 (-0.61)		11.6 (3.63)	0.73	17.27
6	Pop, T	4811 (1.84)		-13 (-1.80)	26.5 (2.85)	0.78	23.46
7	GDP, Pop, T	9225 (2.20)	0.015 (1.32)	-25.42 (-2.17)	37.1 (3.08)	0.80	17.38

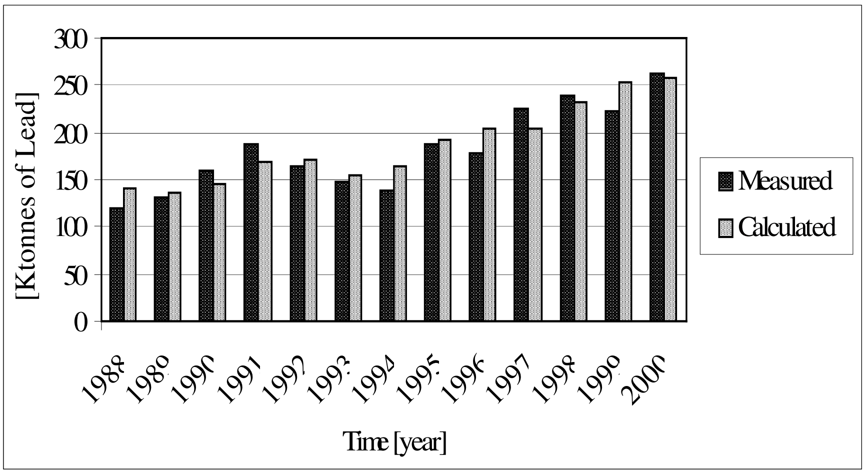

Fig. 3: Measured and calculated inflow of CRT, expressed in ktonnes of Pb

4.4.3 Modelling the future inflow and outflow of CRTs

The future inflow of CRTs is calculated based on the regression model given by Eq. (8) and projected values of the variables GDP and population. Projections are taken from a study for the EU 6th Action Programme [9]. An average GDP growth for the EU by 2.4% per year is projected from 2001 to 2010; slowing to 1.8% per year between 2011 and 2020, and 1.7% per year between 2020 and 2030. The population of the EU is expected to increase slightly during the first decade of this millennium. After 2010, the rate of population growth falls and the population is expected to stabilize after 2020 [9]. The future outflow of CRTs is calculated from the past and future inflow of CRTs and the Weibull distribution of the life span. Figure 4 shows the future inflow and outflow of the CRTs in the EU. The possible substitution of CRTs by flat screen displays is as yet ignored.

4.4.4 Modelling the stock's size of CRTs

The only determinants of the change of the CRT stock over time as described by Eq. (6) are the stock's inflow and outflow, as calculated above. Additional information on the initial magnitude of the stock that is corresponding to the number of TVs and computers owned by people in the EU member states in 1988 is needed. These figures can be found in an UNDP overview (UNDP, 1992). The development in CRT stock size is shown in Fig. 5.

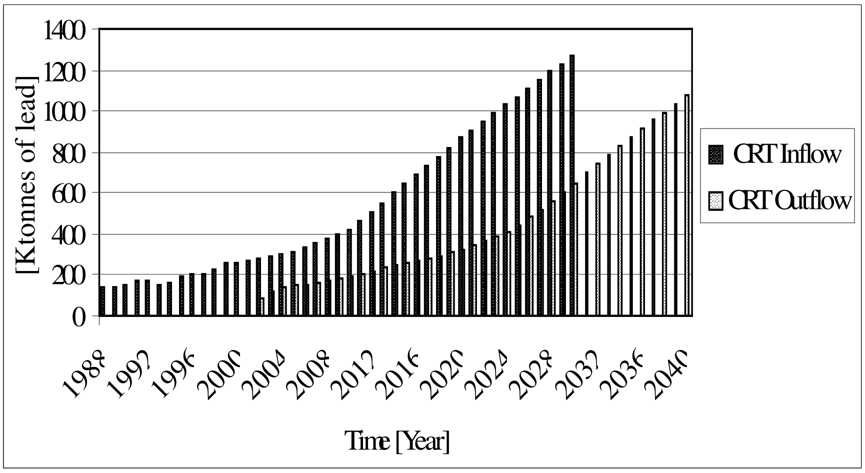

Fig. 4: Projected future inflow and outflow of CRT in the EU, expressed in ktonnes of Pb, based on "baseline scenario", and Weibull distributed life span

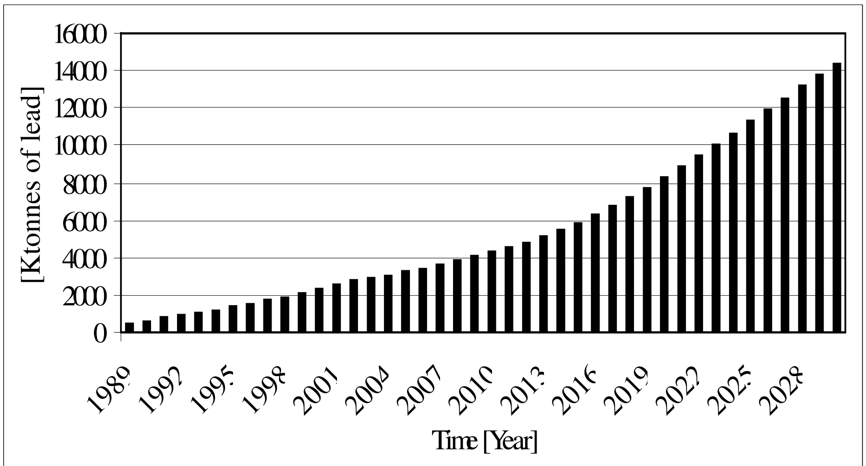

Fig. 5: Amount of lead in the CRT stocks in the EU

4.4.5 Waste stream of CRTs

The draft WEEE states that of the equipment with cathode ray tubes that have been collected, 75% should be recycled or recovered. With a collection rate of 25% or 50% this implies overall recycling rates of 19 to 37.5%. An average value of 26.75% recycling rate has been used in modelling the future recycled stream. It is also assumed that 80% of the remaining waste stream will be landfilled and 20% will be incinerated, which implies that 59% of the total discarded stream will be landfilled and 14.75% will be incinerated. The results of the calculations based on these assumptions are shown in Fig. 6.

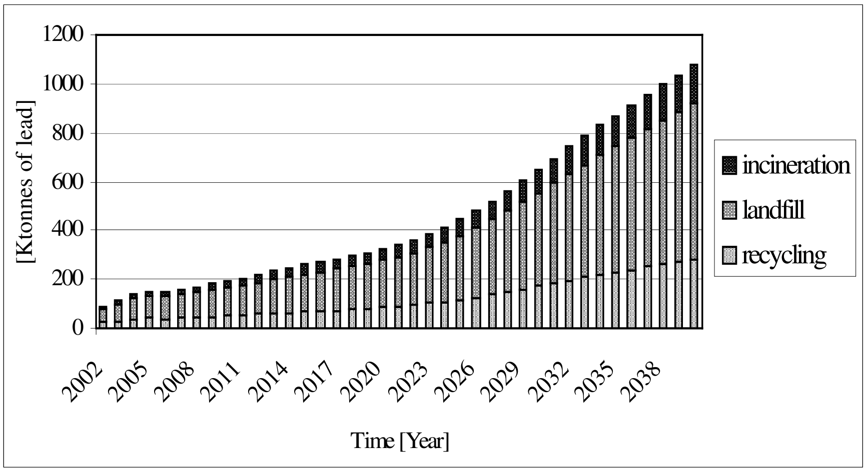

Fig. 6: Future recycled, landfilled, and incinerated lead flows of CRT in the EU

4.5 Conclusions

1. The flows of a certain substance through the economy are basically determined by the economic demand for its applications. This implies that in order to model substance flows, the materials wherein the substance occurs should be a central modelling issue, in turn based on the analysis of the products containing these materials. In contrast, the outflow of the substance out of the economy in the shape of waste and emissions is basically determined by the physical-chemical properties of the substance. These properties determine the losses during use and the possibilities for recycling. A substance flow model therefore must include both economic and physical-chemical variables.
2. In this chapter, a method is presented to model the inflow of products, based on socio-economic variables such as GDP and population size. This method is applied to the case of lead applied in cathode ray tubes.
3. It appears that the model leads to good results: for a time series in the past, the measured inflow compares well to the modelled inflow. In principle, the same model can be used to estimate the future inflow. Not the measured GDP, population etc. but prognoses for these variables then must be used. The model forecasts however are only valid assuming that no unpredicted changes, such as the development of a completely new substitute, will occur. Changes like that will render the inflow model useless.
4. The time variable (T) is used as a proxy to capture the combined influence of other factors such as substitution and technical developments on the inflow. The results have shown that the time variable is an important factor in determining the inflow. The variables implicitly included in T should be investigated further. These variables include technical developments but especially substitution and the driving forces behind that, such as the price of the product or the raw materials and energy embedded in it.
5. In addition, a method is presented to model the product outflow based on two mechanisms: leaching and delay. Leaching refers to emissions of the substance during the use of a product, i.e. by corrosion or volatilisation, and is modelled as a fraction of the total stock of products-in-use. Delay refers to the discarding after use of products, and is determined by the life span of the products. Different distributions can be chosen. In the case of lead in cathode ray tubes, a Weibull distribution was used. The results of the outflow model have not been compared yet with real data.

4.6 Outlook

The model presented in this chapter is a dynamic stock model based on product stock characteristics. The model is meant to be an integral part of a general dynamic substance flow model that can be used to estimate the total environmental consequences of the use of substances in the economic system. At this stage, the model is capable of investigating the main factors determining the dynamic behaviour of a substance, namely the stocks of products containing the substance and its inflows and outflows. The next step is to integrate the models for the different products into one framework at the substance level. The idea is that the result will be more than the sum of its parts. On the one hand, the flow of the substance is also determined by certain characteristics, which can be both functional and economical. On the other hand, recycling can be modelled most adequately at the substance level. In the case of lead, many products contribute to the availability of secondary lead, while the demand for primary lead is influenced by the recycling flow as a whole. This will be the subject of further research. Finally an integration of the substance stock model with a substance flow model will be attempted. The final dynamic substance flow-stock model should include in addition to the use phase, the extraction, manufacturing and waste treatment activities. The stock model should be the central module. For a complete analysis of the environmental consequences of substance flows and stocks in the economic system the energy use in different stages of the system should also be accounted for.

References

Bentum F, Verstappen G, Wagemaker F. Watersysteemverkenningen: Een analyse van de problematiek in aquatisch milieu, report no. 96-023. Netherlands: Ministerie van Verkeer en Waterstaat, 1996.

Bergbäck B, Lohm U. Metals in society. In: Brune D, Chapman V, editors. The global environment - science, technology and management. Oslo: Scandinavian Scientific Press. 1997. p. 276-289.

Boelens J, Olsthoorn A. Software for material flow analysis. In: Vellinga V, Berkhout F, Gupta J, editors. Sustainable sustainability. Dordrecht: Kluwer. 1998. p. 115-130.

Central Bureau of Statistics Netherlands (CBS). Production and trade statistics. Voorburg: Eurostat, 2000.

Gijbels I, Rousson V. A non parametric least square test for checking a polynomial relationship. Statistics & Probability Letters 2001;51(3):253-261.

International Lead and Zinc Study Group (ILZSG). Lead in Batteries. London: ILZSG, 1999.

Kleijn R, Van der Voet E. Chlorine in Western Europe, a MacTempo case study, materials accounting as a tool for decision making in environmental policy. Leiden: Centre of Environmental Science (CML), 1998.

Kleijn R, Huele R, Van der Voet E. Dynamic substance flow analysis: the delaying mechanism of stocks with the case of PVC in Sweden. Ecological Economics 2000;32(2):241-254.

Melo M. Statistical analysis of metal scrap generation: The case of aluminium in Germany. Resources, Conservation and Recycling 1999;26(2):91-113.

Moore D, Tilton J. Economic growth and the demand for construction material. Resources Policy 1996;22(3):179-205.

Research for Man and Environment (RIVM), Economic for the Environment (EFTEC), National Technical University of Athens (NTUA), International Institute for Applied System Analysis (IIASA). European environmental priorities: An integrated economic and environmental assessment, report no. 481505010. Netherlands: RIVM, 2001.

Tiltone J. World metal demand – trends and prospects. Washington D.C.: Resources for the Future, 1990.

Tukker A, Buijst H, Oers L, Van der Voet E. Risk to health and the environment related to the use of lead in products, report no. 00503273. Delft, Netherlands: Organisation For Applied Scientific Research (TNO), 2001.

Udo de Haes H, Van der Voet E, Kleijn R. Substance Flow Analysis (SFA), an analytical tool for integrated chain management. In: Bringezu S, Fischer-Kowalski M, Kleijn R, Palm V, editors. Regional and national material flow accounting: From paradigm to practice of sustainability, Proceedings of the ConAccount Workshop, Leiden, Netherlands, Wuppertal: Wuppertal Institute, 1997. p. 32-42.

United Nation Development Program (UNDP). Human development report. New York: Oxford University Press, 1992.

Van der Voet E. Substance from cradle to grave: Development of a methodology for the analysis of substance flows through the economy and the environment of a region. PhD thesis. Leiden, Netherlands: Leiden University, 1996.