# 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 5 The Environmental and Economic Consequences of the Developments of Lead Stocks in the Dutch Economic System *

## Abstract

This chapter investigates the developments of lead stocks in the Dutch economy and the consequences of such developments for the environment and the economy. The analysis is based on a dynamic substance stock model that combines physical and socio-economic elements. The model estimates lead demand in different applications as a result of the developments in the socio-economic variables. In addition, it estimates the current and future size of lead stocks, the future outflow of discarded lead applications and related emissions, and the availability of lead for future recycling based on the life span, corrosion rate and recycling rate of the lead applications. The results show that the lead inflow is determined by the demand for its individual applications, which in turn are mainly determined either by per capita GDP or by population growth. In future, the societal stock is expected to change from a lead sink to a lead source. The future availability of lead for recycling will exceed its demand. This implies that lead demand in the Netherlands can be met completely by secondary sources. If a similar trend can be found in other countries, a situation of oversupply may arise with adverse consequences for the recycling business and ultimately for the emissions of lead to the environment.

**Keywords**

Substance Flow Analysis; Dynamic Stock Modelling; socio-economic; Lead; Recycling; Resources

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## 5.1 Introduction

Over the last century, the increase of the global population and the growth of the economic activities have been accompanied with an increase of materials demand, and consequently with an increase of extracting, processing, using and waste treatment activities. This has raised the concern about the depletion of resources and the emissions during resources life cycle especially those of heavy metals.

Environmental policies aiming at the reduction of the emission of heavy metals include end-of-pipe processes, but also more integrated measures like the stimulation of recycling and the phasing out of hazardous intended (e.g. lead in gasoline) or not-intended (e.g. cadmium in phosphate fertilizer) applications. Although these policy measures seem to be effective on the short term, their effectiveness on the long term is questionable. A well-known example concerns cadmium recycling. On the short term, recycling may reduce cadmium emissions, however, on the long term these emissions will increase due to the fact that the inflow of cadmium into the economy is supply driven (Huppes et al. 1992). This implies that a reduced demand 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. In this case, policies aimed at phasing out or recycling mercury applications therefore will lead to an increase of its stock in society (Maxson et al. 1991).

This chapter investigates the dynamic behavior of lead stocks in the Dutch economy. Lead has been chosen because it is one of the most extensively used heavy metals in the economic processes on the one hand, and because of its toxic characteristics and its accumulation in the economy on the other hand (Scoullos et al. 2001). In the Netherlands, policy aims at a reduction of lead emissions by phasing out certain lead applications and increasing recycling. On the short term, the phasing-out policy has resulted in a reduction of lead emissions (Tukker et al. 2001), while recycling has led to a reduced landfill of lead containing waste. On the long term, however, both types of measures may have unexpected and undesirable side effects, comparable with cadmium and mercury.

The present chapter investigates the consequences of the past and future developments of lead stocks on the long-term lead management. The cases of cadmium and mercury as mentioned above have been analyzed using Substance Flow Analysis (Van der Voet 1996). These analyses are based on static modelling. It is argued, however, that for long-term management, information is required on the dynamic behavior of substances in the economy (Guinée et al. 1999). Recently, it is acknowledged that including the dynamics in the system is connected to the inclusion of stocks in society (Bergbäck and Lohm 1997). The dynamics of such stocks are very important for the generation of future waste and emissions. Considering stocks so far has resulted in a few specific substance stock inventories or models (Boelens and Olsthoorn 1998; Kleijn et al. 2000). The analysis in this chapter is carried out using a general dynamic substance stock model that combines physical and socio-economic elements.

The chapter is structured as follows. Section 2 will outline the dynamic stock model. In Section 3, a description is presented of the lead applications and the past and future inflows, outflows, and wastes streams of lead are quantified. Section 4 contains the results of the model calculations and Section 5 is dedicated to discussion and conclusions.

## 5.2 Dynamic stock model

Stocks in society refer to the materials, products and infrastructure in use. Large and increasing amounts of materials are stored in such stocks. Stocks of lead can be found, for example, in buildings and in cars. Stocks can be regarded as buffers in the economic system, causing a delay between the inflow of new products and the outflow of discarded products. Phasing out policies aimed at stockbuilding applications thus will become effective only after a certain delay, which could be considerable depending on the exact application.

In general, a substance or material stock is composed out of all the products that contain the substance or material and have a life span longer than 1 year. This could be a large number of products with widely different behavior. This implies that a substance stock model should at least contain two layers: the substance level and the product level. Products are associated with a demand and have a life span, which may or may not be influenced by the substances it contains. A substance in a product may be substituted without changing the demand for the product. The substance in a waste product may be extracted and

recycled, and subsequently applied in different products. As a result, the substance leaves the specific product stock but not society, and the life span of the substance may differ considerably from the life span of each of its applications.
Stocks are continuously renewed. On the one hand, old products are discarded from the stock. On the other hand, new products are bought and become part of the stock. The stock dynamics are determined by this process of renewal. Below, the modelling of the inflow and outflow of the stock is described.

### 5.2.1 Modelling the stock's inflow

The inflow of a certain substance into a stock-in-use is primarily determined by the demand for the products containing the substance. The demand is influenced by socio-economic or economic factors such as Gross Domestic Product (GDP), per capita GDP, population size and growth, inter- and intrasectoral share in GDP, price, consumer taste and preference, substitution and technical developments. In the model, a general function is used to describe the inflow, which is fitted for each product separately based on past trend data (Elshkaki et al., 2002):

$$F^{in}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \tag{1}$$

where $F^{in}(t)$ is the inflow into the product stock at time t, n is the number of explanatory variables, $X_i(t)$ is the socio-economic variable at time t, $\beta_i$ is the model parameter and $\varepsilon(t)$ is the model error at time t.

Sometimes the demand in a certain year does not correspond to the change in the socio-economic variables in the same year, but to changes in these variables some years earlier. Apparently, there is sometimes a time lag between the driving forces and the response. In a mathematical form, this time lag could be accounted for as given by Eq. 2:

$$F^{in}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t-j) + \varepsilon(t) \tag{2}$$

where $X_i(t-j)$ is the socio-economic variable at time (t-j), j is the time lag.

### 5.2.2 Modelling the stock's future inflow

The derived inflow model described by Eq. 1 or 2 can be used further 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 2000). The assumption then is that there is no discontinuity changing the dependency of the demand on the influential variables.

### 5.2.3 Modelling the stock's outflow

The outflow out of the stock takes place through two processes: leaching and delay (Van der Voet et al. 2002). Leaching occurs during use due to corrosion or slow volatilization of substances from various stocks of applications. These emissions may end up in the soil, surface water, groundwater or sewage system. The yearly emissions of a substance in a certain application can be modelled as a fraction of the total size of the stock by linear or exponential emission coefficients. In the model, a linear emission coefficient is used as given by Eq. 3.

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

where $F^{out}{}_E(t)$ is the outflow due to emissions at time t, $C$ is the emission factor and $S(t)$ is the stock at time t.

Delay is related to the discarding of products after use. The discarded outflow of a certain product depends mainly on the product inflow and its life span. The empirical data on the life span is often not available. In that case, the alternative is to assume either an average life span or a certain life span distribution. The discarded outflow could be modelled as a delayed inflow, corrected for the emissions that have taken place during use, as given by Eq. 4:

$$F^{out}{}_D(t) = F^{in}(t-L) - \sum_{i=1}^{L} C \cdot F^{in}(t-L) \cdot (1-C)^{i-1} \tag{4}$$

where $F^{out}{}_D(t)$ is the outflow due to the delay mechanism at time t, $C$ is the emission factor and $L$ being the average life span of the product.
The total outflow at time t, $F^{out}$ then is given by Eq. 5

$$F^{out}(t) = F^{out}{}_D(t) + F^{out}{}_E(t) \tag{5}$$

### 5.2.4 Modelling the stocks

The change of the magnitude of the stock over time is the difference between the inflow and the outflow as given by Eq. 6.

$$\frac{dS}{dt} = F^{in}(t) - F^{out}(t) \tag{6}$$

By knowing the initial value of the stock and the inflow of goods, it is possible to calculate the stock as given by Eq. 7.

$$S(t+1) = S(t) + F^{in}(t) - F^{out}(t) \tag{7}$$

### 5.2.5 Modelling the waste streams

The discarded outflow ($F^{out}{}_D$) will be partly recycled and partly will end up in final waste treatment, either on landfill sites or in incineration plants. Recycled, incinerated, and landfilled streams can be modelled as a fraction of the discarded outflow as given by Eqs. 8, 9 and 10.

$$R(t) = a_1 \cdot F^{out}{}_D(t) \tag{8}$$

$$L(t) = a_2 \cdot F^{out}{}_D(t) \tag{9}$$

$$I(t) = a_3 \cdot F^{out}{}_D(t) \tag{10}$$

where *R(t)*, *L(t)*, and *I(t)* are recycled, landfilled and incinerated streams at time t. The parameters $a_1$, $a_2$, $a_3$ are recycling, landfilling, and incineration fractionation ratios. These fractionation ratios in reality depend on many technical, economical and policy factors.

## 5.3 Description and modelling of lead applications in the Dutch economy

### 5.3.1 Systems definition

Refined lead originates from primary and secondary sources. The most common primary source of lead is galena (lead sulphide, PbS). Lead is often found associated with other heavy metals such as zinc, copper, silver and bismuth. Lead ore is the main source of silver (Scoullos et al. 2001) and bismuth (Graedel 2002). The main source of secondary lead is the recycling of its applications, mainly batteries and lead sheet.
Lead is one of the most extensively used heavy metals in society due to its unique properties such as conductivity, corrosion resistance, density, flexibility, durability and attractive appearance. The largest

application of lead is its use in batteries. Lead in batteries is applied in a variety of products: starting, lighting and ignition (SLI) batteries, traction or stationary batteries and industrial batteries. Traction batteries refer to those batteries that are used to power electric vehicles. The second largest application is lead sheet in building. The third largest application is as a pigment in cathode ray tubes as applied in televisions and computer monitors. Cable sheathing, also a lead containing product, is used for indoor electricity cables in buildings and outdoor electricity, telephones and gas pipes. In the past this used to be a large application. Now it is phased out completely, at least in the Netherlands (Tukker et al. 2001), although still present in old stocks. Furthermore, lead is applied in a number of small products that are used in vehicles such as electronics, wheel weights, glazes, light bulbs, and bronze bushings and bearings. We will refer to this as “Non–battery vehicle applications”.

In addition to its intentional use, lead is present in several products as a contaminant. Lead occurs naturally in trace concentrations in fossil fuels and in phosphate rock. Via phosphate fertilizer it enters the agricultural chain and accumulates there. As a result of processing lead containing waste, it also occurs in residues of waste management such as sewage sludge, compost and products of incineration, i.e. fly ash and bottom ash. These residues sometimes are put to use again. The lead thus enters a secondary, non-intentional life cycle. Fly ash and bottom ash, for example, are used as materials in road construction.

In this chapter, the above-mentioned intentional applications, which account for more than 95% of the total lead inflow in the Dutch economy, are included. They are all applications relevant for a stock model, since their life span exceeds 1 year. The non-intentional applications are not included in the model, because they are generally not associated with stock building. Fig. 1 shows the system of lead flows and stocks in the Dutch society. The stock model as described in Section 2 refers to the stocks-in-use, with their inflows and outflows, as indicated in Fig. 1.

The variables and parameters of the Dutch lead stock model will be described in the following sections.

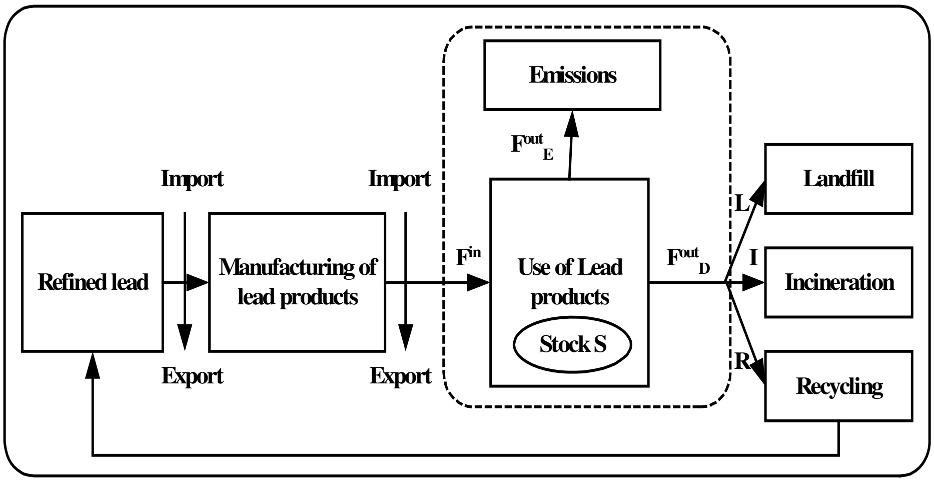


**Fig. 1:** Overall structure of the model.

The consumption phase of the Dutch economy is marked with a dashed line

## 5.3.2 Quantification of the past inflow of lead applications

Fig. 2 shows the past inflow of lead into the stock of products-in-use in the Netherlands from 1988 through 1999.

***Battery system***

The inflow of lead in batteries into the consumption phase is quantified as the number of batteries multiplied by the fraction of the weight that is taken by lead. The lead content of typical SLI, traction or industrial batteries is about 58% of their weights. The inflow of SLI, traction and industrial batteries into the stock-in-use from 1988 through 1999 (Fig. 2) (CBS, 2000; ILZSG, 2000) is the number of produced batteries plus imported batteries minus exported batteries. SLI and traction batteries enter the economy either as separate products or combined with other products, mainly vehicles. The number of SLI and traction batteries corresponding to those products is accounted for as given by Eq. 11.

$$F^{in}(t) = production(t) + [import(t) - \exp ort(t)]_{batteries} + [import(t) - \exp ort(t)]_{vehicles} \quad (11)$$

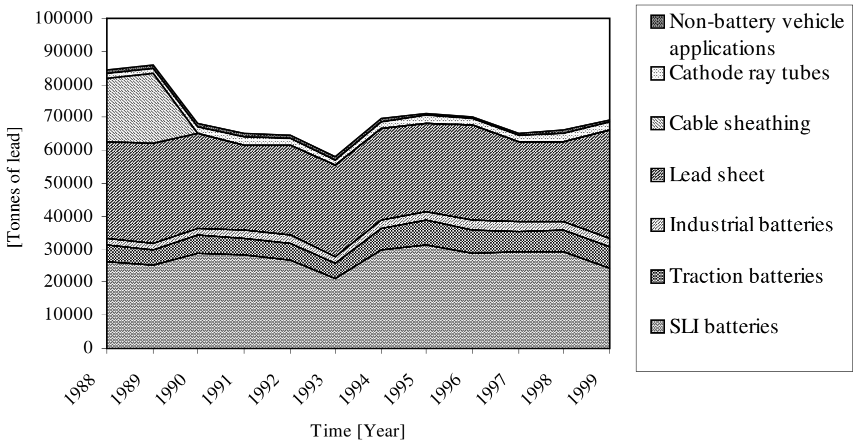


**Fig. 2:** Past inflow of lead products into the stock of products-in-use in the Netherlands, 1988-1999

***Lead sheet in building***

The inflow of lead sheet is quantified in two steps. First, from 1988 through 1999 (Fig. 2) (CBS, 2000; ILZSG, 2000), the inflow is quantified as the produced amount plus the imported minus exported amounts as give by Eq. 12. Second, from 1950 through 1987, the inflow is quantified as the inflow of lead sheet in houses and utility buildings. Lead sheet inflow in houses is quantified based on the newly built houses (Eurostat, 2000) multiplied by an average amount of lead per house. The average amount of lead in each house is estimated as the inflow from 1988 through 1999 divided by 2 (assuming 50% of the inflow is used in houses) divided by the number of newly built houses. The average amount of lead in houses thus is calculated to be 146.95 kg/house.

$$F^{in}(t) = production(t) + [import(t) - \exp ort(t)] \quad (12)$$

***Cable sheathing***

The inflow of indoor cable sheathing from 1950 through 1970, is quantified based on newly built houses (Eurostat, 2000) and an assumption that the amount of lead in cable sheathing equals 1.5 kg/house (Palm, 2002). In the case of outdoor cable sheathing, no information is available that can be used directly to quantify the inflow. However, information is available that can be used to quantify outdoor cable sheathing outflow and stock. The inflow thus can be quantified based on the outflow and the stock. The inflow of outdoor cable sheathing from 1960 through 1990 is quantified as net inflow plus outflow as given by Eq. 13. The net inflow is the difference between stocks in two consecutive years as given by Eq. 14. Cable sheathing outflow and stock are estimated in sections 3.4 and 3.5. Lead is phased out from indoor cable sheathing in 1970 and from outdoor cable sheathing in 1990.

$$F^{in}(t) = F^{net}(t) + F^{out}(t) \quad (13)$$

where $F^{in}(t)$ is the inflow of outdoor cable sheathing at time t, $F^{net}(t)$ is the net inflow at time t, and $F^{out}(t)$ is the outflow of outdoor cable sheathing at time t.

$$F^{net}(t) = S(t+1) - S(t) \tag{14}$$

where *S(t)* is the stock of outdoor cable sheathings at t, and *S(t+1)* is the stock at time t+1
Substitution of Eq. 14 in Eq. 13 gives

$$F^{in}(t) = S(t+1) - S(t) + F^{out}(t) \tag{15}$$

***Cathode Ray Tubes (CRTs)***
Lead inflow in televisions CRTs from 1976 through 1999, in household computers CRTs from 1988 through 1999, and in office computers CRTs from 1989 through 1999 (Fig. 2) is quantified, in the same manner as outdoor cable sheathing, as given by Eq. 15. A CRT contains about 2 kg lead. CRTs outflow and stock are estimated in sections 3.4 and 3.5.

***Non-battery vehicle applications***
The inflow of lead in non-battery vehicle applications (Fig. 2) is quantified as the amount of lead corresponding to the amount or the number of these application in one vehicle (Lohse et al. 2001) multiplied by the number of newly registered vehicles (CBS, 1987-2000).
The amount of lead used per weight for wheel balancing lies between 20 and 25 g as an average. As each vehicle is equipped with 10 weights, this sums up to 200-250 g lead per vehicle. In this study an average of 225 g has been used. Lamps in vehicles contain between 0.2 and 0.75 g lead in the glass bulb, and solder contributes up to 0.2 g lead per lamp. As an average value of 0.4 to 0.5 g lead per bulb is stated. An average vehicle is equipped with 30 to 40 lamps, these sums up to 12-20 g lead per vehicle. Electronics contain about 52.7 g of lead per vehicle. Glazes contain about 1.2 g of lead per vehicle. Bronze bearings and bushings contain about 10 g of lead per vehicle (Lohse et al. 2001). In total, a vehicle thus contains ca. 300 g of lead in small applications.

### 5.3.3 Estimation of future inflow of lead applications

The future inflow of lead into the stock of products-in-use for batteries, lead sheet and non-battery vehicle applications is estimated in two steps. Firstly, we used the regression model as given by Eq. 2 to describe the relationship between the past inflow of lead in each product from 1988 through 1999 and the socio-economic variables (GDP, per head GDP, sectoral share in GDP, lead price, and population size and growth). The regression analysis enables us to test the most significant variables among the socio-economic variables and to eliminate those that do not correlate with the past inflow of the products. The adequacy of the model and the significance of the individual variables are evaluated based on statistical terms such as the adjusted coefficient of determination $R^2$adj, the t-test and the F-statistics. The inflow model equation for each of the lead products as a result of the regression analysis is given in table 1. The results of the regression analysis show that the population size, population growth and per head GDP are the most significant variables. Other variables such as GDP, sectoral share in GDP and lead price are either do not correlate with the inflow (i.e. the adjusted coefficient of determination is low) or insignificant when combined with other variables. Secondly, we used scenario projections of the future development in the most significant variables in the regression model to estimate the future inflow. The projections for the socio-economic variables can be found in (RIVM, 2000). For CRTs, the regression model given by Eq. 2 is used to estimate a relation between the stock of CRTs and the different socio-economic variables.
As has been mentioned in section 2.1, other factors such as consumer's taste and preference, technical development and substitution may affect the inflow, however, these variables are not included in the analysis.

***Battery system***
On a product level, the increase or decrease of Gross Domestic product (GDP) can hardly explain the SLI batteries past inflow trend. The production of lead batteries for new vehicles is expected to fluctuate with the business cycle, but this will not be the case for replacement batteries, which constitute the largest part of the lead batteries market (Tilton, 1999). The results show that this trend could be explained by population growth with a time delay. This is possibly due to an effect of population development on

vehicles sales market and their use. The slightly increasing inflow of industrial batteries could be explained by the developments in the population size but could be explained much better by per capita income development. Per capita income fluctuates in line with the inflow most of the time. Traction batteries are used in different applications with different behavior. Some of them could be effected by the economic growth and others by population developments.

**Table 1:** The inflow model equation for each of the lead applications

| Application | The inflow equation | $R^2$ | F-Statistics |
|---|---|---|---|
| Batteries | | | |
| SLI batteries [a] | Inflow(t) = 18756.0+(0.0957*PopGrowth(t-4)) | 0.34 | 5.3 |
| Traction batteries | Inflow(t) = 236.5+(0.0261*GDP/capita(t)) | 0.76 | 32.0 |
| Industrial batteries | Inflow(t) = 783.0+(0.0076*GDP/capita(t)) | 0.69 | 22.3 |
| | | | |
| Lead sheet | Inflow(t) = 21583.0+(0.0651*PopGrowth(t-14)) | 0.6 | 13.5 |
| | | | |
| Cathode ray tubes (CRTs) | | | |
| CRT- Televisions | Stock(t) = -1.19E7+(1.1760*Pop(t)) | 0.97 | 447.0 |
| CRT- Household computer | Stock(t) = -4.27E7+(2.9420*Pop(t)) | 0.96 | 312.0 |
| CRT- Offices computers | Stock(t) = -2.62E7+(1.8270*Pop(t)) | 0.99 | 1356.0 |
| | | | |
| Non-battery vehicle applications | | | |
| Electronics | Inflow(t) = 109.0+(0.000352*PopGrowth(t-12)) | 0.55 | 15.1 |
| Bronze, bearing and bushings | Inflow(t) = 20.68+(0.000067*PopGrowth(t-12)) | 0.55 | 15.1 |
| Glazes | Inflow(t) = 02.48+(0.000008*PopGrowth(t-12)) | 0.55 | 15.1 |
| Light bulbs | Inflow(t) = 24.82+(0.000080*PopGrowth(t-12)) | 0.55 | 15.1 |
| Weight wheels | Inflow(t) = 465.0+(0.001505*PopGrowth(t-12)) | 0.55 | 15.1 |

[a] Starting, lighting and ignition

### *Lead sheet in building*

The inflow of lead sheet in buildings is directly linked to housing demand, which is mainly driven by the growing population.

**Cathode Ray Tubes (CRTs)**

The demand for CRTs is determined by the demand for televisions, household computers and office computers. The demand for televisions was expected to be driven by the population growth whereas the demand for household computers could be driven by both population growth and economic growth. However, it was difficult to find an equation that can fit the past inflow of televisions and computers. Therefore, we analyzed the relation between the stock size and the socio-economic variables. The results show that the televisions and computers stock size significantly correlate with all of the considered variables. However, the best correlation is the one with the population size. Moreover, the results show that $R^2$adj and F-statistics associated with the three correlation are different. This variation is due to the difference in the three stocks. Although the stock of televisions and the stock of household computers are estimated based on the same number of household, the percentage of households owning a television and those owning a computer are changing overtime in a different manner.

### *Non-battery vehicle applications*

The demand for Non-battery vehicle applications is directly linked to the demand for vehicles, which is mainly determined by population growth and economic growth. The results of regression analysis show the same statistical terms for all non-battery vehicle applications. This is due to the procedure followed in the quantification of their past inflow. The inflow of non-battery vehicle applications is estimated based on the number of newly registered vehicles, which is applied for all these applications, multiplied by the number or the amount of these applications in one vehicle, which is constant overtime.

### 5.3.4 Estimation of the past and future outflow of lead applications

The outflow of lead applications is the sum of the outflow of discarded products and the outflow due to emissions during use. The discarded stream is estimated from the past and future inflow and products life span as given by Eq. 4. The emitted outflow is estimated as a fraction of the stock as given by Eq. 3.
For some applications such as lead sheet, cable sheathing and cathode ray tubes, the outflow will be affected by the initial stock (the stock generated before the available statistical figures of the inflow). The outflow due to the initial stock will be calculated separately, since Eqs. 3 and 4 are not applicable: the age distribution of the initial stock is unknown. It is assumed that the initial stock will be completely discarded and emitted in a number of years, namely the most likely life span for each of these applications (Table 2). Ultimately, the outflow in a certain period is the sum of the outflow due to the initial stock and the outflow due to the known past inflow. The inflows of different applications are those quantified in sections 3.2 and the emission factors and life span for lead applications are given in table 2. The life span is assumed to fit a Weibull distribution. Weibull distribution has been used because it has been shown experimentally that it provides a good fit for many types of life span (Melo, 1999).

**Table 2:** The emission factors, life spans and waste stream distributions of the different lead applications

| Application | Minimum life span (year) | Maximum life span (year) | Most likely life span (year)[b] | Emission during use (%) | Recycling (%)[b] | Incineration (%)[b] | Landfilling (%)[b] |
|---|---|---|---|---|---|---|---|
| ***Batteries*** | | | | | | | |
| SLI [a] | 4 | 7 | 5 | 0 | 95 | 3.5 | 1.5 |
| Traction | 3 | 8 | 5 | 0 | 95 | 3.5 | 1.5 |
| Industrial | 3 | 12 | 10 | 0 | 100 | 0 | 0 |
| ***Lead sheet*** | 45 | 75 | 50 | 0.008[b] | 90 | 2 | 8 |
| ***Cables*** | | | | | | | |
| Indoor | 20 | 45 | 30 | 0 | 75 | - | - |
| Outdoor | 20 | 45 | 30 | 0.025[c] | 75 | - | - |
| ***CRT*** | 10 | 25 | 15 | 0 | 50 | 15 | 35 |
| ***Non-battery applications*** | 2 | 20 | 12 | 0 | 0 | 25 | 75 |

[a] Starting, lighting and ignition
Sources: [b] Tukker et al. 2001, [c] Palm 2002

***Battery system***

The outflow of batteries is only the waste stream. It is assumed that there is no emission during the use phase. The waste stream is estimated as given by Eq. 4.

***Lead sheets in building***

The outflow of lead sheet from stock is the waste flow due to demolishing of buildings or renewing and replacement of sheets. Emission during use takes place as a result of corrosion. The outflow is estimated in two steps because the outflow from the initial stock needs to be calculated separately. First, from 1950 through 1999, the outflow of discarded lead sheet from the initial stock in 1950 is estimated as given by Eq. 16 below, with $\alpha$ = 0.02. Second, from 1996 onward, this outflow is estimated as given by Eq. 4. The second step started at 1996 due to the minimum life span of lead sheet in buildings (45 years) and the first available inflow in 1950. The emissions during use from 1950 onward are estimated as given by Eq. 3.

$$F^{out}{}_{D}(t) = \alpha \cdot [S(1950) - (L_m \cdot C \cdot S(1950))] \tag{16}$$

$$\alpha = 1/L_m \qquad (17)$$

where $F^{out}_D(t)$ is the discarded outflow at time t, $L_m$ is the most likely life span and $C$ is the emission factor

***Cable sheathing***
The outflow of cable sheathing is broken down into the outflow of indoor and outdoor cable sheathing. The outflow of both is estimated in two steps as the discarded sheathings due to demolishing buildings or replacing cables, and the emissions during use for the outdoor cables. The outflow of indoor cables is only the waste stream. It is assumed that there is no emission during the use phase. The outflow of waste indoor cables from 1950 through 1980 is estimated as a fraction of the initial stock in 1950, as given by Eq. 16 with $\alpha$ = 0.033. From 1970 onward, the waste stream is estimated as given by Eq. 4. The outflow of waste outdoor cables from 1960 through 1990 is estimated as a fraction of the initial stock of 1960, as given by Eq. 16 with $\alpha$ = 0.033. From 1980 onward, the waste stream is estimated as given by Eq. 4. The emissions from 1960 onward are estimated as given by Eq. 3.

***Cathode Ray Tubes (CRTs)***
The outflow of CRTs is only the discarded stream with televisions and computers, because no emissions occur during their use phase. The amount of discarded lead in CRTs in televisions as well as in household and office computers are each estimated separately in two steps using the same procedure for the first ten years. First, discarded CRTs from the initial stock in 1975, 1987 and 1988 for televisions, household computers and office computers respectively are estimated as given by Eq. 16. For each of these applications, $\alpha$ = 0.06 in Eq. 16. Next, discarded CRTs are estimated as given by Eq. 4.

***Non-battery vehicle applications***
The outflow of non-battery vehicle applications is the discarded amount with discarded vehicles. The life span of these applications is assumed to be the same as the life span of the vehicle. The stream of discarded non-battery vehicle applications is estimated as given by Eq. 4. It is assumed that no emissions occur during their life time.

### 5.3.5 Estimation of the stocks of lead applications

***Battery system***
The initial stock of lead in SLI batteries in 1998 (Table 3) is estimated as a fraction of the weight that is taken by lead (58%) multiplied by the total number of vehicles in 1998. The development of the stock of lead in batteries from 1998 onwards is estimated as given by Eq. 7.

***Lead sheets in building***
The initial stock of lead sheet in buildings in 1950 (Table 3) is estimated as an average amount of lead of 146.95 kg per house multiplied by total number of houses in 1950, and consequently multiplied by 2 to correct for utility buildings. The development of the stock of lead sheet from 1950 onwards is estimated as given by Eq. 7.

***Cable sheathing***
The initial stock of lead in indoor cable sheathing in 1950 (Table 3) is estimated as an average amount of lead of 1.5 kg per building multiplied by the number of houses in 1950, again multiplied by 2 to correct for utility buildings. The stock of lead in indoor cable sheathing after 1950 is estimated as given by Eq. 7.
The lead stock in outdoor cable sheathing from 1960 through 1990 is estimated as an average amount of lead of 16.7 kg per capita in electricity cables and 12.8 kg per capita in telephones and 0.173 kg per capita in gas pipes, multiplied by the population size (Palm, 2002). The same procedure is used to estimate the initial stock in year 1960 (Table 3). After 1990, the stock is estimated as given by Eq. 7.

***Cathode Ray Tubes (CRTs)***
The lead stock in CRTs in televisions in the period from 1975 through 1999 is estimated as an average amount of lead of 2 kg per television, multiplied by the number of televisions in stock. In turn, the stock of televisions is estimated as the number of household multiplied by the percentage of households owning a

television (CBS, 1975-2000). The same procedure is followed for the estimate of lead stock in CRTs in household computers in the period from 1987 through 1999. For office computers, the number is known and could be applied directly (CBS, 1987-2000). The initial stock of lead in CRTs is the one estimated for the year 1999 (Table 3). After 1999, the stock is estimated as given by Eq. 7.

***Non-battery vehicle applications***

The initial stock of lead in non-battery vehicle applications in 1998 (Table 3) is estimated as an average amount of lead per vehicle multiplied by the number of vehicles in 1998. The stock of lead in non-battery vehicle applications from 1998 onwards is estimated as given by Eq. 7.

**Table 3:** The initial stock of lead in its different applications

| Application | Year | Initial stock (tones of lead) |
|---|---|---|
| Starting, lighting and ignition (SLI) batteries | 1998 | 45600 |
| Lead sheet | 1950 | 640000 |
| Indoor cable sheathing | 1950 | 6530 |
| Outdoor cable sheathing | 1960 | 341000 |
| Non-battery vehicle applications | 1998 | 1800 |
| Cathode ray tubes | 1999 | 26700 |

### 5.3.6 Estimation of the waste streams of lead applications

The lead discarded from the stock of products-in-use will be partly recycled and will partly end up in the final waste treatment, either in landfill sites or in incineration plants. These streams are modelled as given by Eqs. 8, 9 and 10. The discarded outflows are those estimated in section 3.4. The recycling fraction ($a_1$ in Eq. 8), landfill fraction ($a_2$ in Eq. 9) and incineration fraction ($a_3$ in Eq. 10) are given in table 2 (Tukker et al. 2001). We assumed that these fractionation ratios will remain the same in the future.

## 5.4 Results

### 5.4.1 Past and future inflow of lead applications

The results of application of the product stock models described in section 3 show that the inflow of lead in the Dutch economy can be better explained on a product basis than as a total lead inflow due to the number of lead applications, and the different behavior of each application. Fig. 3 shows the total past and future inflow of lead into the stock of products-in-use from 1989 to 2025, broken down to the different applications. The future inflow of SLI batteries is expected to increase from 2000 through 2006 and to stabilize after 2006. The future inflow of industrial batteries and traction batteries are expected to increase over time. The demand for lead sheet is expected to stabilize in the future as a consequence of the stabilization in the demand for houses. In the future, the demand for computers is expected to increase significantly whereas the demand for televisions will be increasing only slightly. The inflow of non-battery vehicle applications is expected to increase from 2000 through 2013 and to stabilize after 2013. In all, the applications for which the inflow can be related to the population growth are expected to stabilize in the future, while the GDP dependent applications will increase further. This is easily explained by the projected development of population and GDP in the RIVM scenario (RIVM, 2000).


**Fig. 3:** Inflow of lead in different applications into the stock of products-in-use in the Netherlands, 1989-2025

### 5.4.2 Outflow of lead applications

Fig. 4a and 4b show the outflows out of the stock-in-use: the discarded applications in 4a and the emissions during use in 4b. As shown in Fig. 4a, the discarding of SLI batteries does not show a general trend. This was to be expected since the inflow is quite stable, and the life span of these batteries is short. However, discarding of traction and industrial batteries is expected to increase due to the increase of the inflow and their long life span. Although the inflow is leveling off, the amount of discarded lead sheet is expected to increase due to the extensive use of lead sheet in the past. Likewise, discarded cable sheathing is expected to keep increasing till the year 2010 due to its extensive use in the past. After 2010 it will start to decrease because it is phased out from some applications in 1970 and from almost all the remaining applications in 1990. Part of the discarded cable sheathings will not be removed from the soil, but will be left in the environment. The amount of discarded CRTs and non-battery vehicle applications is expected to increase. This is due to the extensive and still increasing use of computers and vehicles on the one hand, and to the delay as a result of the long life span of both computers and vehicles on the other hand.

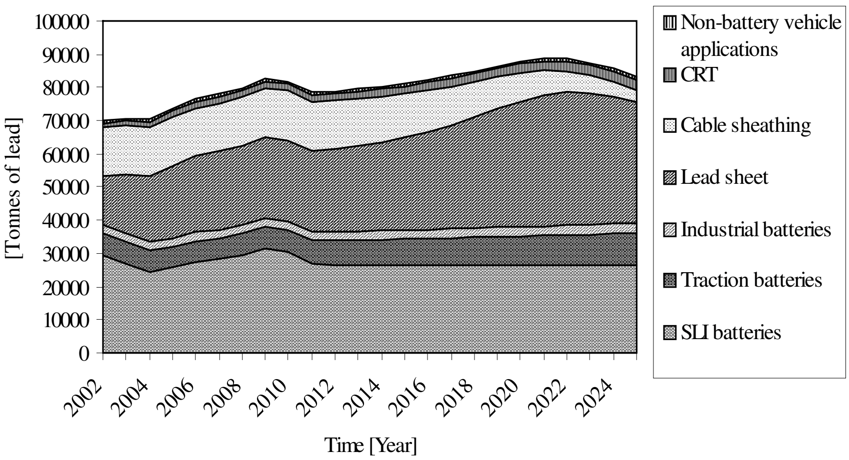


**Fig. 4a:** Discarded outflow of lead applications from the stock of products-in-use, 2002-2025

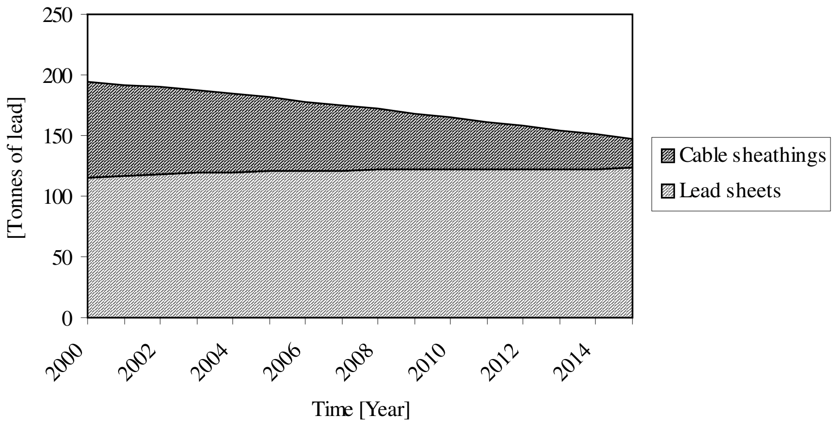


**Fig. 4b:** Emissions of lead applications during use, 2000-2015

Most of the lead applications in stock, such as batteries, CRTs and non-battery vehicle applications, have no emissions during their use phase. Therefore the emissions are mainly due to cable sheathing and lead sheet, which are exposed to the environment. As shown in Fig. 4b, emissions from lead sheet are expected to increase in future due to the expected increase of stock. However, the emissions from cable sheathing stock are expected to decrease slowly over time, as there is no fresh inflow in this stock while part of old stock is being collected and recycled. The remaining amount of cable sheathing in soil is quite high due to the low collection rate and the fact that lead sheathing has a relatively low commercial value. We assumed that 75% of the total amount of cable sheathing in the soil will be taken out. Nevertheless the contribution of cable sheathing to the lead emissions to the environment will remain rather high. The total emissions from the stock are expected to decline. This, however, does not mean that the total lead emissions will decrease. It should be kept in mind that there are other lead emissions to the environment not originating from the stock of products-in-use, especially related to agriculture and to incineration of fossil fuels.

### 5.4.3 Stocks of lead applications

The future development of the stock of lead is shown in Fig. 5. It is clear that lead sheet will dominate the stock-in-use for a long time to come due to the extensive use of lead sheet in the past and its long life span. The stock of SLI batteries is expected to decrease between 2000 and 2011 and will stabilize after 2012. The stock of CRTs is increasing due to the current extensive and increasing use and the relatively long life span. The stock of cable sheathings is decreasing and might be finished by the year 2025. There is no new inflow because cable sheathing is phased out. Most of the stock will become waste and will be partly recycled. The rest will remain in the environment, causing emissions for a long time to come. The stock of non-battery applications is invisible in Fig. 5 due to the fact that the stock of non-battery vehicle applications is and will remain relatively small.

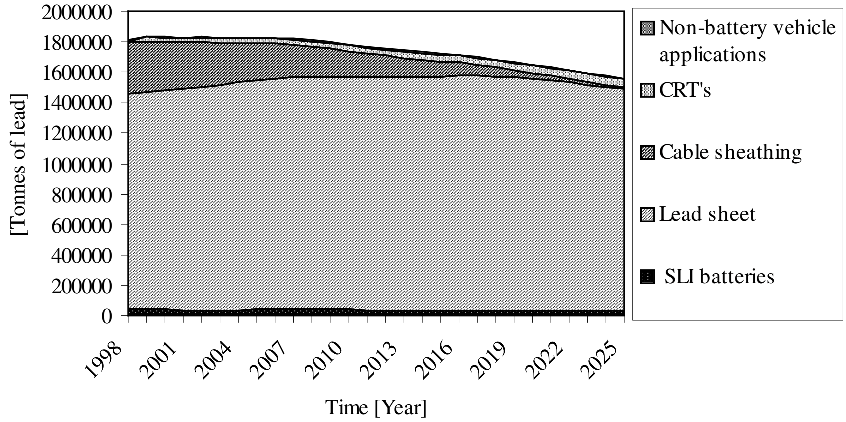


**Fig. 5:** Stock of lead in several products-in-use in the Netherlands, 1998-2025

### 5.4.4 Waste streams of lead applications

By far the largest fraction of the waste stream of lead is recycled. At present, the largest contribution to lead recycling is made by SLI batteries. In future, lead sheet is expected to be the largest contributor: the outflow of SLI batteries is expected to stabilize whereas the outflow of lead sheet will increase. Smaller contributions are made by other batteries: the recycling fraction is equally high or even higher, but the lead flow to these applications is smaller.

The largest flows to landfill and incineration are related to lead sheet, SLI batteries, and CRTs. This can be explained by the intensive use of both lead sheets and SLI batteries in the past and present: the recycling fraction for these applications is quite high, but the amounts are so large that the small percentage of final waste from these applications still amounts to a large quantity compared to others. The flow of waste CRTs has a low recycling fraction. The future flows of CRTs to landfill and incineration is expected to increase and by 2025 will cause almost 20% of the total lead flow to landfills. Flows to incineration and flows to landfill show a rather similar pattern. Only the contribution of lead sheet is different. A larger part of the discarded lead sheet will end up at landfill together with demolition waste, leaving only a very small fraction to be incinerated. The flows of the non-battery vehicle applications to landfill and incineration are relatively high compared to their throughput. This high contribution to the final waste stream is mainly due to low recycling fraction of these applications. The flow of the non-battery vehicle applications is invisible in Fig. 6a due to their relatively small outflow and low recycling fraction. Fig. 6a shows recycled flows of lead applications and 6 b, and c show total waste flows to landfills and incinerators.

### 5.4.5 Future total lead inflow, outflow, stock and waste streams

Fig. 7 shows the total inflow of lead into the stock of products-in-use and the total outflow of lead with discarded products. A remarkable development is that the outflow is larger than the inflow from 2002 onwards. This implies that the stock of lead in products is no longer a sink, but has become a source of lead. Due to the magnitude of the stock (Fig. 5), it can be expected that lead will be coming out of the stock for a long time, even in the case that lead applications would be phased out altogether. This is relevant information for waste management.

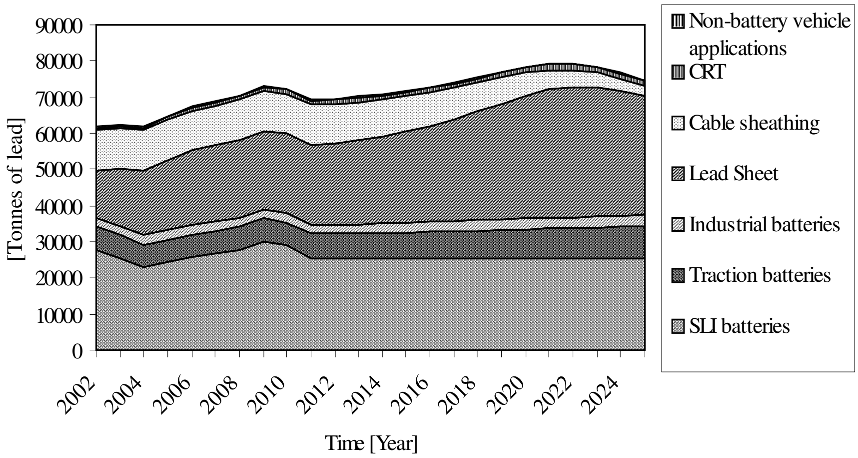


**Fig. 6a:** Flow of discarded lead to be recycled, 2002-2025

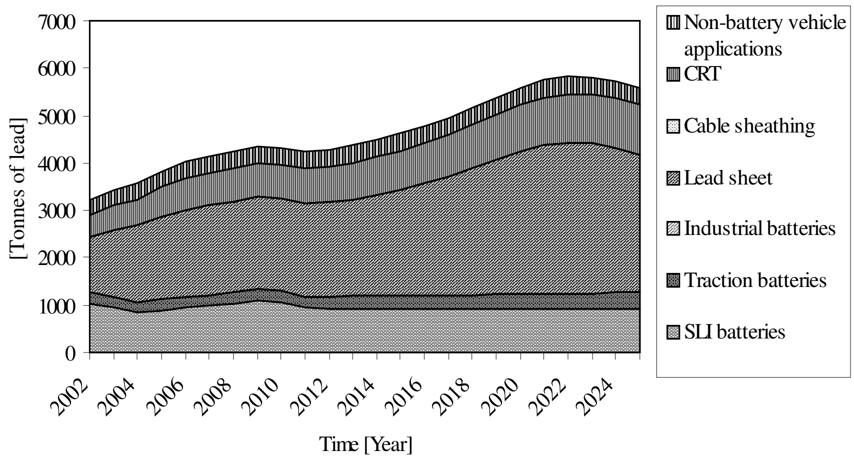


**Fig. 6b:** Flow of discarded lead to Landfill, 2002-2025

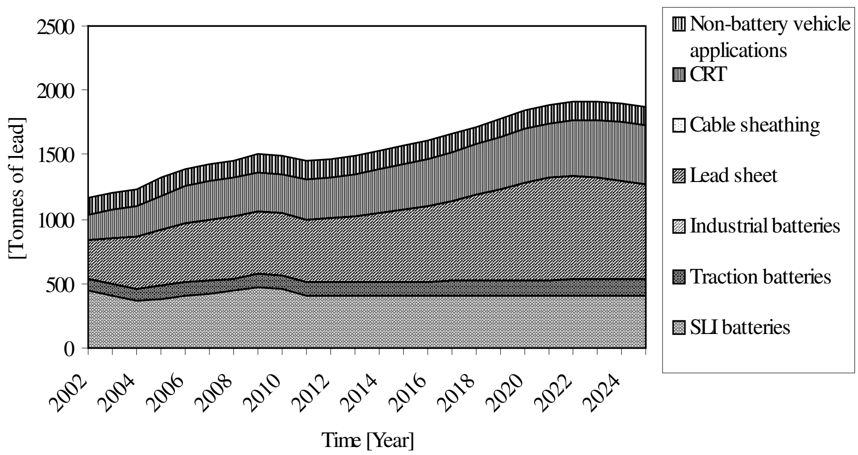


**Fig. 6c:** Flow of discarded lead to be incinerated, 2002-2025

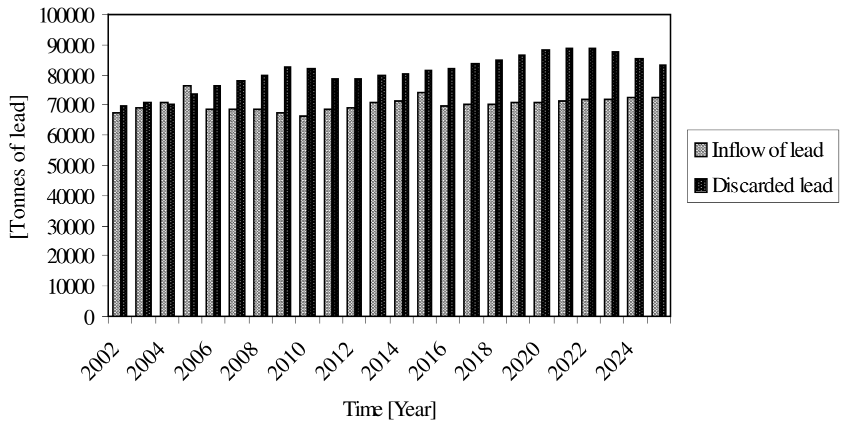


**Fig. 7:** The total inflow of lead into the stock of products-in-use and the total outflow of lead with discarded products, 2002-2025

Although most of the lead applications are recycled (88% of the discarded stream), the amount ending up at landfill sites and incineration plants is still considerable. The percentage of landfill and incineration is even expected to increase slightly. Moreover, there is a significant amount of lead that remains in the environment in old cable sheathing. The remaining amount in soil, which will be almost 5.2% in 2002 will decrease to 4% in 2015. This hibernating stock will still cause diffusive emissions. The expectations for future recycling, landfill, incineration and emissions of lead, as well as the lead remaining in the environment, are shown in Fig. 8.

As stated before, by far the largest part of the lead outflow is recycled. This may have consequences for the future. Fig. 9 shows the future demand for lead applications and the availability of secondary lead.

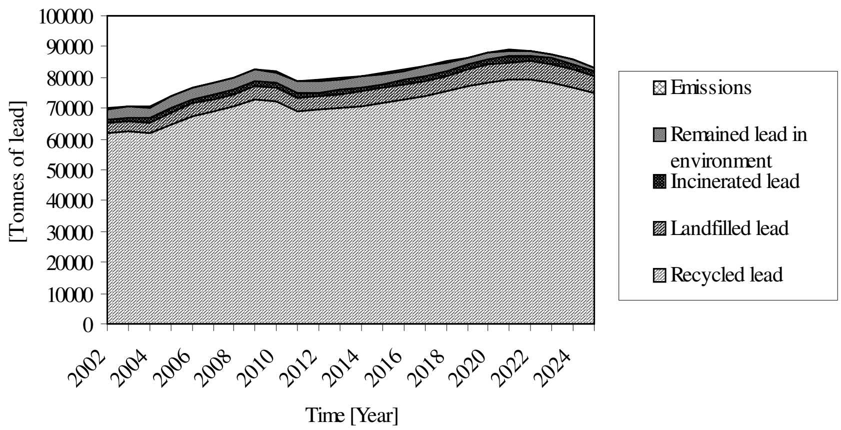


**Fig. 8:** Recycling, landfill, incineration and emissions of lead and lead remaining in the environment, 2002-2025

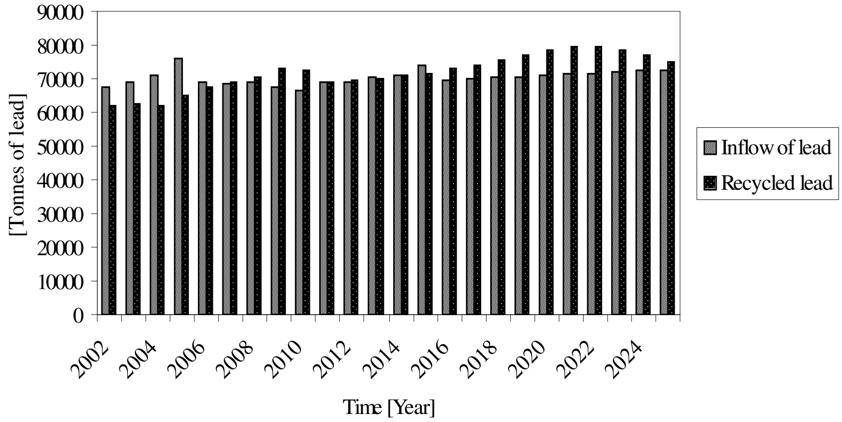


**Fig. 9:** Future demand for lead and the availability of secondary lead, 2002-2025

It is clear that from 2002 to 2006, the demand for lead will be higher than what could be available from recycling. After 2006, the amount of lead to be recycled is expected to exceed the lead demand. This implies that after 2006 the total Dutch demand for lead could be met completely by the generated secondary lead. The dynamics of the production of secondary materials, however, is not confined to one country. The generated waste could be processed outside the studied geographical region and the demand could be met by importing refined lead or lead containing products. Since the analysis is limited to the Dutch economy, which is very open, the possibility that lead available for recycling could exceed its demand need not have large implications. However, when a similar pattern can be found in other countries as well or detected on a larger scale, this would mean that the supply of lead could outgrow the demand. This could have a number of implications. One implication could be a decrease in the lead price. Normally this would lead to an increase in the use, but since lead applications are subject to regulation this might not be so straightforward. On the other hand, it may lead to a decrease in the production of secondary lead, since recycling processes may become less profitable. In turn, this might lead to larger amounts of lead being dumped at landfill sites or being incinerated. This again could lead to larger emissions to the environment.

## 5.5 Discussion and conclusions

The lead model presented in this chapter is a dynamic substance stock model that combines physical and economic elements. By combining physical and economic elements into one model, the limitation of the existing economic and material flow models can be bypassed and their strengths combined. The model operates at two levels: the product level and substance level. This has enabled us to overcome the difficulties of modelling the substance stock: often it is not possible to directly model the substance stock because it is built up out of large number of applications, each showing a different behavior in the economic system.

The model calculates the development of the lead stock over time by the inflow and outflow characteristics of the individual lead applications. For each application, the inflow in the past is modelled as a function of the development in certain socio-economic factors using regression analysis. These factors appear to be sufficient to describe the past inflow. The derived model for the past then is transferred to the future, based on expectations about the development in the socio-economic factors. For the future, however, some other variables such as substitution and technological development might be equally important. These are as yet not included. The forecasts therefore are only valid assuming that no unpredicted changes, such as the development of a completely new substitute, will occur.

The outflow out of the stock of products-in-use is basically determined by two physical processes: leaching and delay. The leaching outflow, emissions during the use of the product, is modelled as a fraction of the stock-in-use. The delay outflow of waste products is modelled as the inflow of some time ago. Two factors play an important role in determining the accuracy of the outcome of the model, namely the emission factors and the life span. The emission factors are assumed to be constant and the life span is assumed to fit a Weibull distribution. In reality both are subject to changes. Moreover, the estimates of both parameters are rather uncertain.

The model estimates the end-of-life treatment in the future - recycling, landfilling and incineration - based on the assumption that the current distribution of the waste stream over the three destinations will remain the same. In reality, these streams are subject to changes because of policy, technical, or economic reasons.

In general, lead flows in waste and emissions should not be treated as final figures for several reasons. First, waste streams contain lead flows from other sources as well, such as waste from mining and industry. Loops and cycles within the end-of-life treatment system make especially the figures for landfill quite uncertain. Second, the model quantifies only part of the emissions from the use phase, while other emission sources such as emissions from extraction, production and waste treatment processes are not included at all.

The lead model includes most of the intentional applications of lead, which constitute the largest part of the societal lead use. However, some other important applications from an environmental point of view, such as lead in ammunition or in fertilizers, are not included. The picture of the emissions to the environment resulting from the stock model is therefore far from complete.

Despite the above mentioned limitations, the stock model provides relevant information for a substance management. The results of this model can be presented in different ways, depending on the policy issue at hand. For example, the contribution of the different applications to landfill or to diffusive emissions can be specified over time, which is useful information for a waste prevention or pollution prevention policy. Another example is the future estimate of what will become available for recycling. From the model calculations it follows that the amount of lead available for recycling will increase and may even become larger than the demand for lead in the near future. This means that at least in the Netherlands the demand will be more than covered by the supply of secondary lead only. To draw a general conclusion, however, the analysis should be made on a larger scale (regional or global) where import and export do not play a big role. If comparable developments can be detected on a larger scale level as well, this may have consequences for the future management of lead. On the one hand, the demand for lead drops due to phase out policies. On the other hand, the supply from secondary sources increases as a result of the past building up of stocks in society. Moreover, the supply from primary sources still continues and is expected to continue for other reasons besides the demand for lead. All this may have consequences for the lead price and thus also for the profitability of primary production as well as the recycling industry. Consequently, this might increase the landfill and incineration streams at the expense of recycling, and ultimately may lead to an increase in the emissions.

The stock model has proven to be applicable and has delivered interesting results that cannot be obtained in any other way. The next step is then to put the stock model as a central module into a general substance flow model. In that way, the picture can be completed and the full implications of the interaction of stocks and flows may become apparent.

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