Development of a dynamic model for Substance Flow Analysis: Part 2 - Integration of stock and flow model

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1 INTRODUCTION

Substance flows and stocks in the economic system (extraction, production, consumption and waste treatment activities) interact in different ways. Some of the substance flows are regarded as a result of the development of the stock, such as the consumption phase outflows (waste flows and emissions). Others are not linked to the stock, but come from short-living applications, nevertheless, these flows are important for estimating the future emissions and waste streams. Substance stocks can be viewed as dependent on flows: the net result of all inflows and outflows through the years. Each flow and stock has its own characteristics of speed, residence time, size and in- and outflow characteristics.

Flows and stocks in the environmental system interact with economic flows and stocks and with each other. Some of these flows and stocks result from the processes in the economic system. Others result from the loops and cycles within the environmental system itself.

Stocks in society mainly exist in the use-phase. The stock model, as developed in Phase 1 of this study, describes the inflow into and the outflow out of the stocks-in-use over time and provides, as a result of that, also an estimate of the size of the stocks. The stock is built up out of all applications of a certain substance with a life span longer than 1 year. The stock model is especially useful to forecast future developments. Its inflow is estimated by regression analysis based on past time series, and its outflow is estimated by the two mechanisms of leaching and delay.

Existing substance flow models describe the inflow into and the outflow out of specific processes in one year. In these models, substance flows in a specific region are estimated from a limited number of fixed values and a lot of model relations. Stocks are usually ignored, just the yearly addition to stock is sometimes specified. To obtain a complete and useful model, both flows and stocks should be included.

To integrate substance flow and stock models, two things must be done:
(1) the flows in and out of the stock must be expressed in yearly flows and the stock's size must be specified per year, and
(2) the flows which are not linked to the stock should be specified over time to cover the same time period.

The first issue has been taken care of already when defining the stock model in Phase 1 of this study. This model is set up in such a way that inflows and outflows are specified per year over time. Thus, the yearly flows can be integrated in a flow model, which operates on a yearly basis. The second issue is related to the fact that the stock model operates over a long period of time. Not only the stock related flows, but also the non-stock related flows therefore must be specified over time, as time series of inflows and outflows of economic processes.

For some of these flows, which in a one-year model normally would have fixed values, time series can be estimated by regression analysis. Other flows can be estimated as model relations assuming that these relations are valid over time.

Our main objective in Phase 2 of this study, of which this is the report, is to develop an integrated flow-stock model and to implement the developed model for lead flows and stocks in the Dutch economic system.

To develop a general dynamic substance flow model, the main influential factors in determining the dynamics of the in- and outflow of the substance in the different stages in the economic system should be identified. Some of these factors are related to the developments in the world market, while others are related to the developments in the domestic market. Therefore, two models are needed, a country model in which these stages are specified in details and a world model which is required to estimate trends in the demand for the substance and the substance containing product and serve as a background for the country model. In the analysis, it will be mentioned whether the explanatory variable that is affecting the dynamic behavior of the substance in the production of the refined substances, production of substance containing applications, consumption and waste management subsystems is valid for the world or just the country.

The report is structured as follows: In Chapter 2, the general mathematical modelling of the extraction and production phases is discussed. In Chapter 3, the mathematical modelling of the consumption phase is described. Chapter 4 treats the modelling approach for waste treatment activities (recycling, incineration and landfilling) and the main factors that determine their dynamics. Chapter 5 outlines the integration of the stock and flow model for lead in the Dutch economy. The specification of model parameters and the application of the model for lead in the Netherlands can be found in chapter 6. Chapter 7 contains a general discussion, conclusions and recommendations.

2 PRODUCTION PROCESSES

In the production phase of substances containing applications, the change of the magnitude of the substance's stock overtime is the difference between the substance inflow and its outflow. A stock may exist in the production phase, however, this stock can be ignored and the change of the magnitude of the substance's stock overtime can be assumed equal to 0 as given by Eq.1. Therefore, the inflow of substances into the production of different applications is equal to the total outflow from the production processes (emissions and products) as given by Eq. 2. Flows connected to the production processes are shown in figure 1.

$$\frac{dS_{PP}(t)}{dt} = 0 = F_{PP}^{in}(t) - F_{PP}^{out}(t) \tag{1}$$

$$F_{PP}^{in}(t) = F_{PP}^{out}(t) \tag{2}$$

F^{in}_{PP} *(t)* is the total inflow of a substance into the production processes of all applications at time t, F^{out}_{PP} *(t)* is the total outflow of a substance from the production processes of all applications at time t.

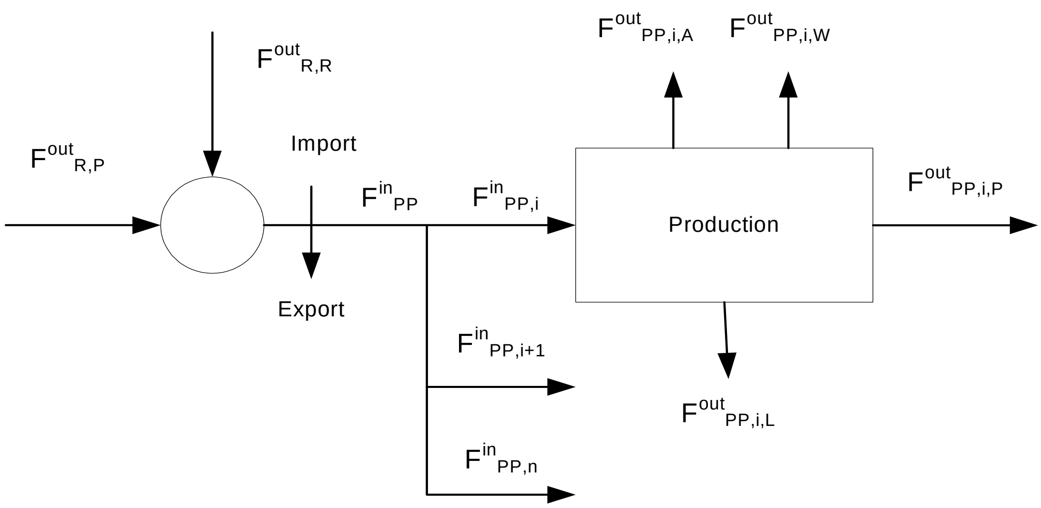

Figure 1: Flows connected to the production processes

$\mathbf{F^{out}_{R,R}}$ is the produced secondary refined substance, $\mathbf{F^{out}_{R,P}}$ is the produced primary refined substance, $\mathbf{F^{in}_{PP}}$ is the total inflow of a substance into the production processes of all applications, $\mathbf{F^{in}_{PP,i}}$ is the inflow of the substance into the production process of product i, $\mathbf{F^{out}_{PP,i,P}}$ is the outflow of the substance in the produced product i, $\mathbf{F^{out}_{PP,i,A}}$ is the outflow of the substance to the air during the production process of product i, $\mathbf{F^{out}_{PP,i,W}}$ is the outflow of the substance to the water during the production process of product i, and $\mathbf{F^{out}_{PP,i,L}}$ is the outflow of the substance to the landfill sites from the production process of product i.

2.1. Inflow of substances into the production processes

The inflow of a substance into the production processes is the total amount required to produce different products as given by Eq.3.

$$F_{PP}^{in}(t) = \sum_{i=1}^{n} F_{PP,i}^{in}(t) \quad (3)$$

F^{in}_{PP} *(t)* is the total inflow of a substance into the production processes of all applications at time t, $F^{in}_{PP,i}$ *(t)* is the inflow of the substance into the production process of product i at time t and n is the number of products .

For each application, the inflow of the substance into the production process is equal to the outflow of the substance in the produced product plus the other outflows from the production process (air emissions, water emissions, and waste flow) as given by equation 4.

$$F_{PP,i}^{in}(t) = F_{PP,i,P}^{out}(t) + F_{PP,i,A}^{out}(t) + F_{PP,i,W}^{out}(t) + F_{PP,i,L}^{out}(t) \quad (4)$$

$F^{in}_{PP,i}$ *(t)* is the inflow of the substance into the production process of product i at time t, $F^{out}_{PP,i,P}$ *(t)* is the outflow of the substance in the produced product i at time t, $F^{out}_{PP,i,A}$ *(t)* is the outflow of the substance to the air during the production process of product i at time t, $F^{out}_{PP,i,W}$ *(t)* is the outflow of the substance to the water during the production process of product i at time t, and $F^{out}_{PP,i,L}$ *(t)* is the outflow of the substance to the landfill sites from the production process of product i at time t.

The inflow of a substance F^{in}_{PP} into the production processes within a country is the amount of the substance produced in the country (primary and secondary) plus the imported amount of the substance minus the exported amount as given by Eq. 5.

$$F_{PP}^{in}(t) = F_{R,R}^{out}(t) + F_{R,P}^{out}(t) + import(t) - \exp ort(t) \quad (5)$$

$F^{out}_{R,R}$ *(t)* is the produced secondary refined substance in the country at time t, which is known from the recycling processes, $F^{out}_{R,P}$ *(t)* is the produced primary refined substance in the country at time t.

To determine the inflow of the substance into the production processes F^{in}_{PP}, on the basis of Eq. 5 the import and export of the substance should be known and possible to estimate in the future. Alternatively, the inflow could be estimated directly for each product as a balancing item of the production process as given by Eq. 4, if the other flows are known. Due to the difficulties in the future estimates of the import and export of substances, and the difficulties in distributing the total inflow, which can be estimated from equation 5, to different products, the inflow will be estimated directly as a balancing item as given by Eq. 4 and the total inflow of the substance will be estimated as given by Eq. 3. This implies also that not supply but demand is the driving force: the domestic and foreign demand for products containing the substance.

2.2. Outflow of substances from the production processes

The total outflow of the substance from the production processes is the amount of the substance in the produced products, the emissions during the production processes, and the waste flow to landfill.
The amount of the substance in each product in the past is known. For the future, it can be estimated either on the basis of explanatory variables or a certain scenario. The amount of the substance in each product is determined by the produced products and the substance content of the product.
The production of a certain product in a specific country is determined by the global demand for products and the competition in the world market as effected by energy cost, labor cost indicated by GDP/C, and the cost of disposing of any residual material. The substance content of a product is determined by substitution and technical developments. The amount of the substance in each product (the outflow of products multiplied by the fraction of the weight that is taken up by the substance) can be estimated on the basis of the explanatory variables.
Regression analysis can be used to establish a relation between the outflow of products from the production processes within the country and the most influential factors.

In the model, a general function (Eq. 6) is used to describe the outflow of the substance in products based on the past trend data.

$$F_{PP,i,P}^{out}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \qquad (6)$$

$F^{out}_{PP,i,P}$ *(t)* is the outflow of the substance in the produced product i at time t, *β's* are the regression parameters, *Xi's* are the explanatory variables, and ε is the model error.

The other outflows can be estimated as a fraction of the outflow of the substance in products as given by Eqs. 7, 8 and 9.

$$F_{PP,i,A}^{out}(t) = \alpha_{PA,i}(t) \cdot F_{PP,i,P}^{out}(t) \qquad (7)$$

$$F_{PP,i,W}^{out}(t) = \alpha_{PW,i}(t) \cdot F_{PP,i,P}^{out}(t) \qquad (8)$$

$$F_{PP,i,L}^{out}(t) = \alpha_{PL,i}(t) \cdot F_{PP,i,P}^{out}(t) \qquad (9)$$

$\alpha_{PA,i}$ *(t)* is the air emission factor at time t, $\alpha_{PW,i}$ *(t)* is the water emission factor at time t and $\alpha_{PL,i}$ (t) is the landfilling factor at time t.

The other outflows are estimated as a fraction of the outflow of the substance in products, however, these flows can be estimated as a fraction of the inflow, if it is possible to find information on this relation.

2.3. The main influential aspects affecting the production industry

2.3.1. The demand for products

The global demand for a product is an important factor in determining their production level. When the global demand for certain products is increased, the production is expected to increase to meet this demand, however, in a country level, this could be the case if products can be produced in a competitive way. The world demand of a specific product can be used as indicator.

2.3.2. The price of energy and labor cost

The price of energy and labor cost determine for a large extent, the product price and therefore, the competitiveness in the world market. The energy price can be used directly as indicator for the energy cost and the wages or per capita GDP can be used as indicator for labor cost.

2.3.3. Technological development

Technological developments may also play an important role by enhancing the substitution or minimizing the content of the substance in the application without changing the performance. Moreover, technical development may play import role in determining the parameters used in the model equations.

2.4. Import and export of primary and secondary substances

The import and export of primary and secondary substances can be estimated as the difference between the produced primary and secondary refined substance in a country and the inflow of substances (primary and secondary) into the production processes of the substances containing applications. In most cases, the production of refined substances (primary and secondary) is possible to estimate in the future (see the recycling processes (4.1.3.2)). The inflow of these substances into the production processes of their applications (see 2.1) is not available directly, however, it is possible to estimate the inflow as described in section 2.1. By estimating the inflow directly from Eq. 4, the value of the import minus the export can be estimated from Eq. 5. It is difficult to separate the estimated value as import and export, therefore, the estimated value will remain as one variable, the net import.

3 THE USE PHASE

The consumption subsystem includes two types of applications, stock-building applications (applications with a life span of more than one year) and short-living applications (applications with a life span of one year and less). For both, intentional as well as non-intentional applications can be identified. In the following sections, the mathematical modelling of the consumption phase will be described.

3.1. Intentional applications of substances

3.1.1. Stock-building applications

Stock building applications refers to those applications with a life span of more than one year. These applications have been discussed in the report of Phase 1 of this study, however, a general description of the modelling part will be repeated here.

3.1.1.1. 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. 10.

$$\frac{dS_C}{dt} = F^{in}{}_C(t) - F^{out}{}_C(t) \tag{10}$$

3.1.1.2. 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:

$$F_C^{in}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t-j) + \varepsilon(t) \tag{11}$$

Where $F^{in}{}_C(t)$ is the inflow into the product stock at time t, *Xi's* are the socio-economic variables at time (t-j), j=0,1,2,….., *β's* are the model parameters and *ε(t)* is the model error at time t.

3.1.1.3. Modelling the stock's future inflow

The derived inflow model described by Eq. 11 can be used further to estimate the future inflow of goods. Projected values of the influential variables are then required. The assumption then is that there is no discontinuity changing the dependency of the demand on the influential variables.

3.1.1.4. Modelling the stock's outflow

The outflow out of the stock takes place through two processes: leaching and delay. 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 as given by Eq. 12.

$$F^{out}{}_{C,E}(t) = C \cdot S(t) \tag{12}$$

Where $F^{out}{}_{C,E}(t)$ 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. 13:

$$F^{out}{}_{C,D}(t) = F^{in}{}_{C}(t - L_U) - \sum_{i=1}^{L_U} C \cdot F^{in}{}_{C}(t - L_U) \cdot (1 - C)^{i-1} \tag{13}$$

Where $F^{out}{}_{C,D}(t)$ is the outflow due to the delay mechanism at time t, C is the emission factor and L_U being the life span of the product in use.

The total outflow at time t, $F^{out}{}_{C}$ then is given by Eq. 14

$$F^{out}{}_{C}(t) = F^{out}{}_{C,D}(t) + F^{out}{}_{C,E}(t) \tag{14}$$

3.1.1.5. Modelling the hibernating stock

The term "hibernating stock" refers to the stock of goods no longer providing the service they are made for, but not thrown away yet. Some goods are stored for some time before being discarded. The main difference between the stock-in-use and the hibernating stock lies in the product life span. In the use phase, the life span is determined by the technical specification of the product. In the hibernating phase, however, the life span is determined by the consumer's decision.

If a certain product is stored before being discarded, this hibernating time should be taken into account, either by adding the hibernating time (L_H) to the use time (L_U), if all the discarded outflow enters the hibernating stock, or by modelling the hibernating stage separately.

If the hibernating stage is to be modelled separately, the change of the magnitude of the hibernating stock is the difference between its inflow and outflow as given by Eq. 15.

$$\frac{dS_H}{dt} = F^{in}{}_H(t) - F^{out}{}_H(t) \qquad (15)$$

$F^{in}{}_H\,(t)$ is the inflow to the hibernating stock at time t and $F^{out}{}_H\,(t)$ is the outflow from the hibernating stock at time t.

The inflow to the hibernating stock ($F^{in}{}_H$) is the discarded outflow of the stock-in-use ($F^{out}{}_{C,D}$) or part of it as given by Eq. 16.

$$F_H^{in}(t) = \alpha_H \cdot F_{C,D}^{out}(t) \qquad (16)$$

α_H is the fraction of the discarded outflow of the stock-in-use which is entered the hibernating stock.

The outflow from the hibernating stock is the outflow due to the emission during hibernation ($F^{out}{}_{H,E}$) and the discarded outflow ($F^{out}{}_{H,D}$). The same mathematical equations used for modelling the use outflow (Eq. 12 and 13) can be used. L_U in Eq. 13 should be replaced by the hibernating time (L_H).
Alternatively, Eq. 13 can be used directly and the life span is the use life span plus the hibernating life span.

3.1.2. Short-living applications

Short living applications refer to those applications with a life span of a year or less. These applications do not contribute to the stock building in the economic subsystem, however, they are also important, similar to the stock-building applications, as a cause of emissions and accumulation in the environment. For these applications, the use sometimes equals the emissions to the environment. This is the case with lead as applied in ammunition: once the bullets are used, lead is brought directly to the environment.

3.1.2.1. 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. 17. Although the stock might be present, it is ignored in the model. For the short-living application, the change of the magnitude of the stock is equal to 0, since the time resolution of the SFA model generally is 1 year. Therefore, the inflow is equal to the outflow as given by Eq. 18.

$$\frac{dS_C}{dt} = F_C^{in}(t) - F_C^{out}(t) = 0 \qquad (17)$$

$$F_C^{in}(t) = F_C^{out}(t) \qquad (18)$$

3.1.2.2. Modelling the inflow

The demand for short-living products containing the substance can be modelled in the same way as the demand for the stock-building applications. In the model, a general function is used to describe the inflow, which is fitted for each product separately based on past trend data:

$$F_C^{in}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \tag{19}$$

Where $F^{in}_C(t)$ is the inflow at time t, *Xi's* are the socio-economic variables at time (t), *β's* are the model parameters and $\varepsilon(t)$ is the model error at time t.

Sometimes, it is not possible to find information on the past inflow of the substance in a certain application, however, information on the total use of the substance in all applications including the unknown application might be known. In this case, the inflow might be estimated on the basis of the total use of the substance and the use of the substance in the other applications (balancing item). For the future, the total demand for the substance should be modelled in addition to the separate applications. This is can be done only if data for one application is missing.

3.1.2.3. Modelling the future inflow

The derived inflow model described by Eq. 19 can be used further to estimate the future inflow of the short-living applications. Projected values of the influential variables are then required. The assumption then is that there is no discontinuity changing the dependency of the demand on the influential variables.

3.1.2.4. Modelling the outflow

The outflow of the short-living applications is the outflow due to emissions and the discarded outflows. As has been mentioned above, sometimes the use equals the emissions to the environment. In some cases, an explicit borderline between the economy and the environment has to be made: is the bullet the emission, once shot, or only the corrosion from it once it lays there on the soil? (see 7.2.1) Outflow by discarding is also a possibility, only for the short-living applications there is no delay to be considered.
The yearly emissions of a substance in a certain application can be modelled as a fraction of the inflow or as the inflow completely as given by Eq. 20.

$$F_{C,E}^{out}(t) = \alpha \cdot F_C^{in}(t) \tag{20}$$

Where $F^{out}_{C,E}(t)$ is the outflow due to emissions at time t, α is the emission factor and $F^{in}_C(t)$ is the inflow at time t.

The discarded outflow (if any) is the total outflow, which is equal to the inflow (Eq. 18), minus the emission outflow as given by Eq. 21:

$$F_{C,D}^{out}(t) = F_C^{in}(t) - \alpha \cdot F_C^{in}(t) = F_C^{in}(t) \cdot (1 - \alpha) \qquad (21)$$

Where $F^{out}{}_{C,D}(t)$ is the discarded outflow at time t.

If the outflow is assumed to be the emission to the environment only (i.e. α=1), thus, the discarded outflow is equal to zero.

The total outflow at time t, $F^{out}{}_C$ then is given by Eq. 22.

$$F^{out}{}_C(t) = F^{out}{}_{C,D}(t) + F^{out}{}_{C,E}(t) \qquad (22)$$

3.2. Non-intentional applications of substances

In addition to the substances' intentional use, substances exist in applications as contaminants. This presence is either due to the natural occurrence of substances in ores, such as the presence of lead in phosphate fertilizers, fossil fuels and other heavy metals, or it is due to anthropogenic sources, such as the presence of lead in sewage sludge and incineration and recycling residues.
For the non-intentional applications, the inflow of substances in the economic system is not related to the substance itself but rather to the application that the substance occurs in. In this case each application has to be modelled separately. In some cases, applications have well developed models and/or scenarios, which can be used directly. In other cases, however, a model has to be made on the basis of explanatory variables related to the application.
Just as the intentional applications of substances, the non-intentional applications are either short-living applications or stock-building applications. Both will be discussed below.

3.2.1. Non-intentional stock-building applications

Substances occur non-intentionally in stock-building applications. These applications could be a side-effect of the intentional use of the substance itself, for example lead occurring in construction materials as a result of application of incineration residues (bottom ash and fly ash), which are contaminated with lead from municipal waste. Non-intentional stock-building applications could also be other substances' or materials' intentional applications, for example the occurrence of lead in zinc or steel applications.
In the case that the substance occurs non-intentionally due to the initial intentional use of the substance itself, the inflow of the substance in the economic system is in fact a re-entry. The substance starts its second life-cycle as a contaminant in materials made from waste treatment residues, after its first life-cycle as an intentional product that has reached the waste stage. Therefore, this re-entry can be modelled as the outflow of the recycling and incineration of the intentional applications as described in section 4.1 and 4.2 . In this case, the substance content of the application is determined by technical factors such as the technical specifications of the recycling or incineration plants. The outflow of these applications is determined again by the two mechanisms of leaching and delay. The same equations described in section 3.1.1 can be used to estimate the stock and the outflow.
In the case that the substance occurs non-intentionally due to the use of intentional stock-building applications of other materials, the inflow of the concerned substance is related to these other materials. The inflow of the substance can be estimated from the inflow of the other material's applications and its technical specification of the smelting and refining processes. The inflow of these applications can be estimated on aggregated level based on the explanatory variables described in 3.1.1.
The outflow is also determined by the two mechanisms of leaching (emissions during use) and delay (discarding). Emissions during use can be modelled, as described in the report of Phase 1, as a fraction of the stock-in-use. The amount of the concerned substance in the waste stream is determined by the inflow into the stock and the delay due to the life span of these applications. Different assumptions can be made to estimate the life span. These are also treated in the report of Phase 1.

3.2.2. Non-intentional short-living applications

Substances also occur non-intentionally in short-living applications (applications with a life span of one year or less). These applications could, just as the non-intentional stock-building applications, be a side-effect of the intentional use of the substance itself (lead in sewage sludge) or could be due to the natural occurrence of the concerned substance in other substances' ores (lead in other heavy metals ores, lead in fertilizers and fossil fuels).
In the case that the substance occurs non-intentionally in recycled waste treatment residues, the inflow of the substance in the economic system is the outflow of the intentional applications model as described in sections 3.1.1 and 3.1.2.
In the case that the substance occurs naturally in other materials, the inflow and outflow of the concerned substance is linked to the applications of these materials. Sometimes, models and/or scenario's for the inflow of these applications are available, especially for the energy sector. If not, a model has to be built using the equations presented in section 3.1.2.

4 WASTE MANAGEMENT

The discarded outflow (F^{out}_D) from the stock of products in use and/or the hibernating stock will be partly collected for recycling purposes and partly will end up in final waste treatment, either on landfill sites or in incineration plants. Collected, incinerated, and landfilled streams can be modelled as a fraction of the discarded outflow as given by Eqs. 23, 24 and 25.

$$F_{SC}^{in}(t) = a_1(t) \cdot F_{C,D}^{out}(t) \tag{23}$$

$$F_L(t) = a_2(t) \cdot F_{C,D}^{out}(t) \tag{24}$$

$$F_I(t) = a_3(t) \cdot F_{C,D}^{out}(t) \tag{25}$$

$$a_1(t) + a_2(t) + a_3(t) = 1 \tag{26}$$

Where $F^{in}_{SC}(t)$ is the amount of scrap waste material, which is domestically collected for recycling purposes, at time t, and $F_L(t)$, and $F_I(t)$ are the landfilled and incinerated streams at time t. The parameter $a_1(t)$ is the collection rate which is determined by world market and country policy and the parameters $a_2(t)$, $a_3(t)$ are the landfilling, and incineration rates. These rates in reality depend on many technical, economical and policy factors.

4.1. Recycling

4.1.1. Introduction

Recycling of materials and reuse of products is a way to minimize the extraction flow by extending the resource life, minimize the amount of waste to be incinerated and/or landfilled, and compared to primary production, the energy needed for the recycling processes is less.

Although recycling has many advantages, it is not necessarily an attractive option from environmental point of view (Kandelaars, 1998). Recycling has emissions and waste of its own. It can be associated with the same level of extraction and sometimes an increase in recycling may increase the total emissions of CO_2 due to the increased need for transporting waste to the recycling center.

Recycling of materials involves several interconnected processes (Fig. 2). The recycling process begins with the collection of old scrap from obsolete products followed by sorting and separation activities and ended by smelting and refining processes. Each process has its own requirements (material, energy), recoveries and losses (waste and emissions). The processes will be discussed in the following paragraphs.

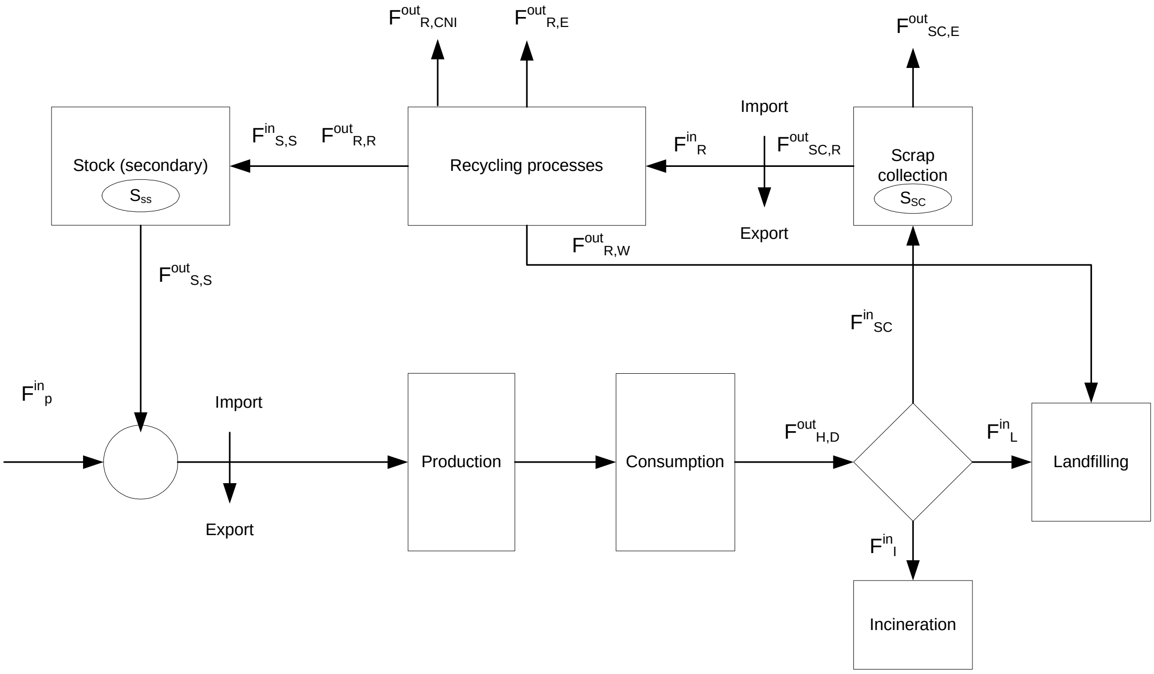

Figure 2: The main processes in the recycling industry

$\mathbf{F^{out}_{C,D}}$ discarded outflow from the stock in use, $\mathbf{F^{in}_{sc}}$ is the inflow of collected scrap, $\mathbf{F^{out}_{SC,E}}$ is the emitted outflow, $\mathbf{F^{out}_{SC,R}}$ is the outflow which goes to the recycling processes, $\mathbf{F^{in}_{R}}$ is the inflow of scrap to the recycling processes within the country, $\mathbf{F^{out}_{R,E}}$ is the emitted outflow, $\mathbf{F^{out}_{R,W}}$ is the landfilled outflow, $\mathbf{F^{out}_{R,CNI}}$ is the waste outflow which is used in other applications (non-intentional applications), $\mathbf{F^{out}_{R,R}}$ is the substance secondary outflow, $\mathbf{F^{in}_{S,S}}$ is the inflow of secondary material to the stock of secondary material and $\mathbf{F^{out}_{S,S}}$ is the outflow of secondary material from the stock.

Recently, the recycling of materials has been increased in the developed as well as the developing countries. Due to the geographical and economic conditions, the developed countries have a high collection rate and developing countries have a high utilization rate (Beukering, 2001). The increase in recycling is related to different factors. In some countries, the increase is related to the high disposal cost and an increase of public awareness, while in other countries economic reasons are the main cause of the increase.

The recycling industry is determined by market driven factors such as the cost involved in the different processes and the price of primary material compared to the price of secondary material. It is also determined by technical factors such as the purity and homogeneity of collected products scrap and the quality of recycled material. Moreover, policy, which reflects the public awareness and the environmental factors, is playing an important role in determining the recycling process. These factors will be explained and related to different stages in the recycling process below.

4.1.2. The main influential aspects affecting the recycling industry

4.1.2.1. Availability of resources

The availability of resources has direct impact on the recycling industry. In general, countries that have a high resource availability tend to recycle less and those with less resource availability tend to rely more on the utilization of secondary materials. Although the availability of resources might not affect the collection of old scrap, it will mainly affect negatively the recycling processes (sorting, smelting and refining) within the country and the reliance on the secondary materials in the production processes (utilization). The availability of resources can be indicated by the per capita primary material production (metal ore production/capita).

4.1.2.2. Material demand

The global demand of the material is an important factor in determining the collection rate and the utilization rate. When the global demand for a certain material is increased, the recycling rate will increase to meet this demand especially when the material in a global level is scarce. The world demand of a specific material and the world reserve can be used as indicator.

4.1.2.3. The price of secondary material compared to the price of primary material

The price of secondary material is an important factor in the producer's decision, when they have to choose between the primary and secondary materials for their production processes. It is more likely that the producers will use the secondary material if the price of these materials is lower than that of the primary material. Consequently, the utilization of the secondary material will increase. Scrap collection might be affected more by the collection cost rather than the change in the price of secondary materials. The primary/secondary price ratio can be used as indicator.

4.1.2.4. The price of energy

It is known that the primary production requires more energy than the secondary production. For example, processing metal ores requires more energy than the secondary production of metals because in scrap, the metal is already in its metallic form. Therefore, it is likely that if the energy price goes up or in countries that rely on import for their energy requirements, the utilization of secondary materials will be higher. To evaluate the effect of energy price on the recycling industry, either the energy price can be used directly as indicator, or the net import of energy can be used (Beukering, 2001).

4.1.2.5. Collection and transportation cost

The collection and transportation cost have a direct impact on the collection of old scrap. If the collection cost goes up, the collection of old scrap will decrease. The collection cost is partly affected by the governmental policy, for example by subsidizing collection or by a deposit system.

4.1.2.6. Labor cost

The recycling industry is known as a labor-intensive activity. If the wages in a certain country are high, the collection, sorting, smelting and refining of materials will be affected negatively. The wages or per capita GDP can be used as indicator.

4.1.2.7. Public awareness

For several reasons, high-income level is associated with strong environmental awareness and is closely correlated with strict environmental regulation (Beukering, 2001). Per capita GDP can be used as indicator.
The level of income as indicated by GDP/capita has different effects on the recycling industry. A high level of income will enhance the recycling activities, at the same time, it indicates that the labor cost is also high. This is therefore a dual effect. Which one is more likely to affect the recycling industry will be empirically determined. (Berglund, 2002).

4.1.2.8. Population density

Countries with high population density could have a high recycling rate. High population density may increase the land price and consequently increase the landfill cost. Moreover, people living in densely populated areas are more conscious about waste management (Berglund, 2002).

4.1.2.9. Landfill tax

Landfill tax is a policy instrument to minimize the waste stream to landfill. If the landfill cost increases, the collection of old scrap for recycling will increase as well.

4.1.2.10. The availability of scrap

The availability of scrap in large quantities will affect the recycling industry positively. If the scrap is available in large quantities, the price of the scrap might decrease and thus the recycling of such scrap will be profitable.

4.1.2.11. Technical aspects

Several technical aspects are playing role in determining the efficiency of the collection of old scrap and the utilization of materials. The purity and homogeneity of the old scrap are determining the collection rate and the purity of the secondary materials and the possibility of using the material in the same products again are determining the utilization rate.

4.1.3. Modelling the recycling processes flows and stocks

4.1.3.1. Scrap collection

Scrap collection is a stage where the collected scrap from obsolete product is stored for some time before either being exported or entering the recycling processes.

4.1.3.1.1 Scrap stock

The change of the magnitude of the scrap stock overtime is the difference between the inflow (the collected scrap from obsolete products) and the outflow (the exported scrap, the emitted outflow during the storage time and the scrap utilized inside the country) as given by Eq. 27.

$$\frac{dS_{SC}(t)}{dt} = F_{SC}^{in}(t) - F_{SC}^{out}(t) \tag{27}$$

S_{sc} is the stock of scrap in the scrap collection stage, F^{in}_{sc} is the inflow of collected scrap and F^{out}_{sc} is the outflow of scrap to the recycling processes, the emission during storage and export.

4.1.3.1.2 Scrap inflow

The inflow of scrap to the scrap collection stage is the old scrap collected from obsolete products. The collected scrap is a fraction of the discarded outflow from the stock-in-use or the hibernating stock as given by Eq. 28. The collected stream is mainly determined by policy, economic, technical and socio-economic aspects, as elaborated below.

$$F_{SC}^{in}(t) = a_1(t) \cdot F_{C,D}^{out}(t) \tag{28}$$

With $F^{in}_{SC}(t)$ is the amount of waste material domestically collected for recycling purposes at time t and $a_1(t)$ is the collection rate.

The economic factors, indicated by the ratio of primary material price and secondary material price, are mainly determining to what extent the recycling process is profitable. The price of secondary material could be used as a proxy for the cost involved at this stage (the cost of scrap collection and transportation). The effect of the policy can be tested and regulated in the model by the different policy measure such as landfill tax and collection system availability and cost. For example, to minimize the amount of waste that is landfilled in the Netherlands, the government has increased the landfill tax from 10 G/Ton in 1980 to 250 G/Ton in 2000. This increase in the landfill tax will increase the disposal cost and consequently will effect the collection of old scrap positively. The socio-economic and demographic factors can be indicated by per capita GDP and population density. The technical aspects such as the homogeneity and purity of scrap could be captured by the prices.

Regression analysis can be used to establish the relation between the collection rate of each of the substance's applications and the different influential factors (material demand, the cost of collection and transport, Pop density, Per capita GDP, Landfill tax). In the model, a general function (Eq. 29) is used to describe the collection rate which can be fitted for each product separately based on the past collection rate trend data.

$$a_1(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \tag{29}$$

β's are the regression parameters, *Xi's* are the explanatory variables, and ε is the model error.

4.1.3.1.3 Scrap future inflow

The derived collection rate model described by Eq. 29 can be used further to estimate the future collection rate. Projected values of the influential variables are then required. The assumption then is that there is no discontinuity changing the dependency of the collection rate on the influential variables. The future inflow of scrap can be estimated as given by Eq. 28 based on the future collection rate and the future discarded outflow from the stock-in-use.

4.1.3.1.4 Scrap outflow

The outflow from the collected scrap phase is the outflow due to emissions during the storage time and the utilized flow within the country or outside the country (export) as given by Eq. 30.

$$F_{SC}^{out}(t) = F_{SC,E}^{out}(t) + F_{SC,R}^{out}(t) \tag{30}$$

$F^{out}_{SC}(t)$ is the outflow from the scrap collection stage at time t, $F^{out}_{SC,E}(t)$ is the emitted outflow at time t and $F^{out}_{SC,R}(t)$ is the outflow which goes to the recycling processes at time t.

The outflow to the recycling processes can be estimated as delayed inflow as given by Eq. 31. The storage time could range from 0 to a few years. The outflow due to the emissions during the storage time can be estimated as a fraction of the scrap stock as given by Eq. 32.

$$F_{SC,R}^{out}(t) = F_{SC}^{in}(t - L_{SC}) - \sum_{i=1}^{L_{SC}} \alpha_{SC} \cdot F_{SC}^{in}(t - L_{SC}) \cdot (1 - \alpha_{SC})^{i-1} \tag{31}$$

$$F_{SC,E}^{out}(t) = \alpha_{SC} \cdot S_{SC}(t) \tag{32}$$

α_{SC} is the emission from the scrap and L_{SC} is the storage time of the scrap in this stage.

Sometimes, the life span of the collected scrap (L_{SC}) in the storage phase is not known. In this case, it is possible to assume that the inflow in a certain year is the same as the outflow in the same year (i.e. the stock is neglected).

4.1.3.2. Recycling processes

The recycling processes stage includes sorting, smelting and refining of old scrap. At this stage, the change of the magnitude of the stock over time is the difference between the inflow and the outflow and equal to 0 as given by Eq. 33. Therefore, the inflow of scrap to the recycling processes (the outflow from the scrap collection stage) is equal to the outflow from the recycling processes (emissions, waste and useable secondary materials) as given by Eq. 34.

$$\frac{dS_R(t)}{dt} = 0 = F_R^{in}(t) - F_R^{out}(t) \tag{33}$$

$$F_R^{in}(t) = F_R^{out}(t) \tag{34}$$

4.1.3.2.1 Inflow to the recycling processes

The inflow of the old scrap F^{in}_R to the recycling processes (sorting, smelting and refining) within the country is determined by the outflow from the scrap collection stage $F^{out}_{SC,R}$ and the import and export of old scrap as given by Eq. 35.

$$F_R^{in}(t) = F_{SC,R}^{out}(t) + import(t) - \exp ort(t) \tag{35}$$

To determine the inflow of scrap to the recycling processes within the country (F^{in}_R), either the import and export (net import) in Eq. 35 should be known and possible to estimate in the future and the past collected flow is known, or the inflow should be estimated directly as a balancing item of the recycling processes as given by Eq. 34. In the model, the later will be used to estimate the inflow of lead to the recycling processes, due to the difficulties in the estimates of the future import and export and the difficulties in finding information on the past discarded and collected flow for all products. This implies also that not supply but demand is the driving force: the domestic and foreign demand for the substance.

4.1.3.2.2 Outflow from the recycling processes

The outflow from the recycling processes is the emissions during the recycling processes, the waste flow to landfill, the waste flow which is used for other applications (non intentional flow of substance) and the useable secondary materials as given by Eq.36.

$$F_R^{out}(t) = F_{R,E}^{out}(t) + F_{R,W}^{out}(t) + F_{R,CNI}^{out}(t) + F_{R,R}^{out}(t) \tag{36}$$

$F^{out}_R(t)$ is the total outflow of the substance from the recycling processes time t, $F^{out}_{R,E}(t)$ is the emitted outflow at time t, $F^{out}_{R,W}(t)$ is the landfilled outflow at time t, $F^{out}_{R,CNI}(t)$ is the waste outflow which is used in other applications (non-intentional applications) at time t and $F^{out}_{R,R}(t)$ is the substance secondary outflow at time t.

The usable secondary material is estimated on the basis of explanatory variables. Regression analysis can be used to establish a relation between the outflow of secondary

materials from the recycling processes within the country and the most influential factors. In general, policy, plant capacity, international contracts and agreements, and the world market determine the outflow of secondary materials. The most influential aspects to be considered are: sorting and transformation cost, the cost of disposing of any residual material, energy cost, labor cost indicated by GDP/C, availability of capital, recycling plant capacity indicated by the number of plants and the capacity of each one, demand (the global demand for the material), and the price of secondary material compared to the price of primary material.
In the model, a general function (Eq. 37) is used to describe the outflow based on the past trend data.

$$F_{R,R}^{out}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \qquad (37)$$

β's are the regression parameters, *Xi's* are the explanatory variables, and ε is the model error.

Each one of the other outflows from the recycling processes can be estimated as a fraction of the outflow of secondary materials as given by Eqs. 38, 39 and 40.

$$F_{R,E}^{out}(t) = \alpha_{RE}(t) \cdot F_{R,R}^{out}(t) \qquad (38)$$

$$F_{R,L}^{out}(t) = \alpha_{RL}(t) \cdot F_{R,R}^{out}(t) \qquad (39)$$

$$F_{R,CNI}^{out}(t) = \alpha_{CNI}(t) \cdot F_{R,R}^{out}(t) \qquad (40)$$

$F^{out}_{R,R}$ *(t)* is the outflow of secondary materials from the recycling processes within the country at time t and *α's (t)* are the emission, landfilled waste, used waste, factors at time t.

The other outflows are estimated as a fraction of the outflow of the refined substance from the recycling processes, however, these flows can be estimated as a fraction of the inflow of scrap, if it is possible to find information on this relation.

4.1.3.2.3 Future outflow from the recycling processes

The derived outflow model described by Eq. 37 can be used further to estimate the future outflow from the recycling processes. Projected values of the influential variables are then required. The assumption then is that there is no discontinuity changing the dependency of the outflow on the influential variables. The future other outflows from the recycling processes can be estimated as given by Eqs. 38, 39, and 40.

4.1.3.3. Secondary material market

4.1.3.3.1 Stock of secondary materials

The change of the magnitude of the stock of the secondary material over time is determined by the inflow of secondary material and the outflow as given by Eq. 41.

$$\frac{dS_{SS}(t)}{dt} = F_{SS}^{in}(t) - F_{SS}^{out}(t) \tag{41}$$

4.1.3.3.2 Inflow of secondary materials

The inflow of secondary material into the stock is the outflow from the recycling processes (Eq.42).

$$F_{SS}^{in}(t) = F_{R,R}^{out}(t) \tag{42}$$

4.1.3.3.3 Outflow of secondary materials

The outflow of secondary material from the stock is determined by the world market and technical aspects and can be modelled as a fraction of the stock as given by Eq.43. Regression analysis can be used to determine the most influential aspects in determining this flow. In practice, the most influential aspects are the purity of the recovered material, resources availability and the price of secondary material compared to the price of primary material.
In the model, a general function (Eq. 44) is used to describe the fraction of the stock which is used in the production processes based on the past trend data.

$$F_{SS}^{out}(t) = \alpha_{SS}(t) \cdot S_{SS}(t) \tag{43}$$

$$\alpha_{SS}(t) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i(t) + \varepsilon(t) \tag{44}$$

4.2. Incineration

The incineration process of substances containing products is an option of the waste management of substances. At this stage, the change of the magnitude of the stock over time is the difference between the inflow of substances from different sources in the economic system and the outflow and equal to zero as given by Eq. 45. Therefore, the inflow of substances into the incineration plants is equal to the outflow of substances from these plants as given by Eq. 46.

$$\frac{dS_{inc}(t)}{dt} = F_{inc,t}^{in}(t) - F_{inc,t}^{out}(t) = 0 \tag{45}$$

$$F_{inc,t}^{in}(t) = F_{inc,t}^{out}(t) \tag{46}$$

where $F^{in}_{inc,t}$ (t) is the total inflow of the substance into the incineration plants from different sources at time t and $F^{out}_{inc,t}$ (t) is the total outflow from the incineration plants at time t.

4.2.1. The inflow of substances into the incineration plants

The inflow of substances into the incineration plants mainly comes out of the stock-in-use of different substances applications. This flow is estimated together with the inflow of substances to be landfilled for each application as the difference between the total discarded waste stream from the stock-in-use of these applications and the collected flow for recycling as given by Eq. 47.

$$F^{in}_{inc,land,i}(t) = F^{in}_{inc,DC,i}(t) + F^{in}_{land,DC,i}(t) = F^{out}_{C,D,i}(t) - F^{in}_{SC,i}(t) \quad (47)$$

where $F^{in}_{inc,land,i}$ is the inflow of the substance into the incineration plants and landfill sites together from the discarded product i, $F^{in}_{inc,DC,i}$ is the inflow of the substance into the incineration plants from the discarded product i, and $F^{in}_{land,DC,i}$ is the inflow of the substance into the landfill sites from the discarded product i.

The discarded outflow $F^{out}_{C,D,i}(t)$ is estimated as given by Eq. 13 and the collected scrap $F^{in}_{SC,i}(t)$ as given by Eq. 28.

The inflow of substances into the incineration plants from the discarded products is estimated as a fraction of the total not-collected flow for each product as given by Eq. 48. This fraction is determined by several factors such as policy, the characteristics of the waste stream and others. In the model different scenarios can be used to estimate the inflow of substances into the incineration plants.

$$F^{in}_{inc,DC,i}(t) = \alpha_{1,i}(t) \bullet F^{in}_{inc,land,i}(t) \quad (48)$$

$\alpha_{1,i}$ is the fraction of the total not collected flow of product t that ends up in the incineration plants

The total inflow of substances into the incineration plants is the inflow of substances from the discarded products and the inflow from other sources as given by Eq. 49.

$$F^{in}_{inc,t}(t) = \sum_{i=1}^{n} F^{in}_{inc,DC,i}(t) + F^{in}_{inc,others}(t) \quad (49)$$

where $F^{in}_{inc,others}$ is the inflow of substances into the incineration plants from other sources than the discarded products.

Other inflows into the incineration plants such as the incinerated flow of sewage sludge can be estimated as model relations.

4.2.2. The outflow of substances from the incineration plants

The total outflow of substances from the incineration plants is equal to the inflow of these substances into the incineration plants. The outflow of substances from the incineration plants is the amount of these substances in the incineration residues (bottom and fly ash) and the emissions during the incineration process (Eq. 50). Each one of these outflows is estimated as a fraction of the total inflow of the substance into the incineration plants as given by Eqs. 51, 52, and 53.

$$F_{inc,t}^{out}(t) = F_{inc,B}^{out}(t) + F_{inc,F}^{out}(t) + F_{inc,E}^{out}(t) \quad (50)$$

$$F_{inc,B}^{out}(t) = \beta_1(t) \bullet F_{inc,t}^{in}(t) \quad (51)$$

$$F_{inc,F}^{out}(t) = \beta_2(t) \bullet F_{inc,t}^{in}(t) \quad (52)$$

$$F_{inc,E}^{out}(t) = \beta_3(t) \bullet F_{inc,t}^{in}(t) \quad (53)$$

$\beta_1 + \beta_2 + \beta_3 = 1$

$F^{out}_{inc,,t}$ is the total outflow of substances from the incineration plants, $F^{out}_{inc,,B}$ is the outflow of substances from the incineration plants in bottom ash, $F^{out}_{inc,,F}$ is the outflow of substances from the incineration plants in fly ash and $F^{out}_{inc,,E}$ is the emissions of substances from the incineration plants.

The distribution of substances between the different outflows is determined by the technical specifications of the incineration plants.

4.3. Landfilling

The landfilling of substances containing products is an option of the waste management of substances. At this stage, the change of the magnitude of the stock over time is the difference between the inflow of substances from different sources in the economic system and the outflow of these substances to the environmental compartments (soil and ground water) as given by Eq. 54.

$$\frac{dS_{land}(t)}{dt} = F_{land,t}^{in}(t) - F_{land,t}^{out}(t) \quad (54)$$

where $F^{in}_{land,t}$ (t) is the total inflow of the substance into the landfill sites from different sources at time t and $F^{out}_{land,t}$ (t) is the total outflow from the landfill sites at time t.

4.3.1. The inflow of substances into the landfill sites

The inflow of substances into the landfill sites originates from different sources in the economic system. These are the stock-in-use, recycling processes, production processes, and the consumption of non-intentional applications of substances.

The inflow of substances into the landfill sites from the stock-in-use is estimated together with the inflow of substances to be incinerated. Both are estimated as the difference between the total discarded waste stream from the stock-in-use and the collected flow for recycling as given by Eq. 47. The inflow of substances into the landfill sites from the discarded products is estimated as a fraction of the total not-collected flow of each product as given by Eq. 55.

$$F_{land,DC,i}^{in}(t) = (1 - \alpha_{1,i}(t)) \bullet F_{inc,land,i}^{in}(t) \qquad (55)$$

where $F^{in}_{land,DC,i}$ is the inflow of the substance into the landfill sites from the discarded product i and $F^{in}_{inc,land,i}$ is the inflow of the substance into the incineration plants and landfill sites together from the discarded product i.
The total inflow of substances into the landfill sites is the inflow of substances from the discarded products and the inflow from other sources as given by Eq. 56.

$$F_{land,t}^{in}(t) = \sum_{i=1}^{n} F_{land,DC,i}^{in}(t) + F_{land,others}^{in}(t) \qquad (56)$$

where $F^{in}_{land,others}$ is the inflow of substances into the landfill sites from other sources than the discarded products.

Other inflows into the landfill sites such as the landfilled flow from the sewage sludge, landfilled flow from incineration residues, and others can be estimated as model relations.

4.3.2. The outflow of substances from the landfill sites

The outflow of substances from landfill sites is the amount of these substances leached to the soil and ground water. The leaching outflow is estimated as a fraction of the stock of substances in the landfill sites as given by Eq. 57.

$$F_{land}^{out}(t) = \delta(t) \bullet S_{land}(t) \qquad (57)$$

5 DEFINING THE INTEGRATED SUBSTANCE FLOW AND STOCK MODEL FOR LEAD IN THE NETHERLANDS.

5.1. Introduction

Flows and stocks in the economic system interact in different ways. Some of the substance flows in the economic system are result of the developments of the stock. Some other flows, such as the flows related to the substance's non-intentional applications and the emission flows and waste streams from other economic activities (extraction, processing, and loops and cycles within the end-of life treatment system), are not linked to the stock. Nevertheless, these flows are important for the estimate of the future emissions and waste streams. On the other hand, substance stocks in the economic system can be viewed as dependent on flows: the net results of all inflows and outflows through the years.

Flows and stocks in the environmental system interact with economic flows and stocks and with each other. Some of these flows and stocks result from the processes in the economic system. Others result from the loops and cycles within the environmental system itself. Flows and stocks in the economic system and those of the environmental system resulted from the processes of the economic system are shown for lead in figure 3.

In this chapter, some attention will be given to the relation between lead flows and stocks in the economic and environmental systems.

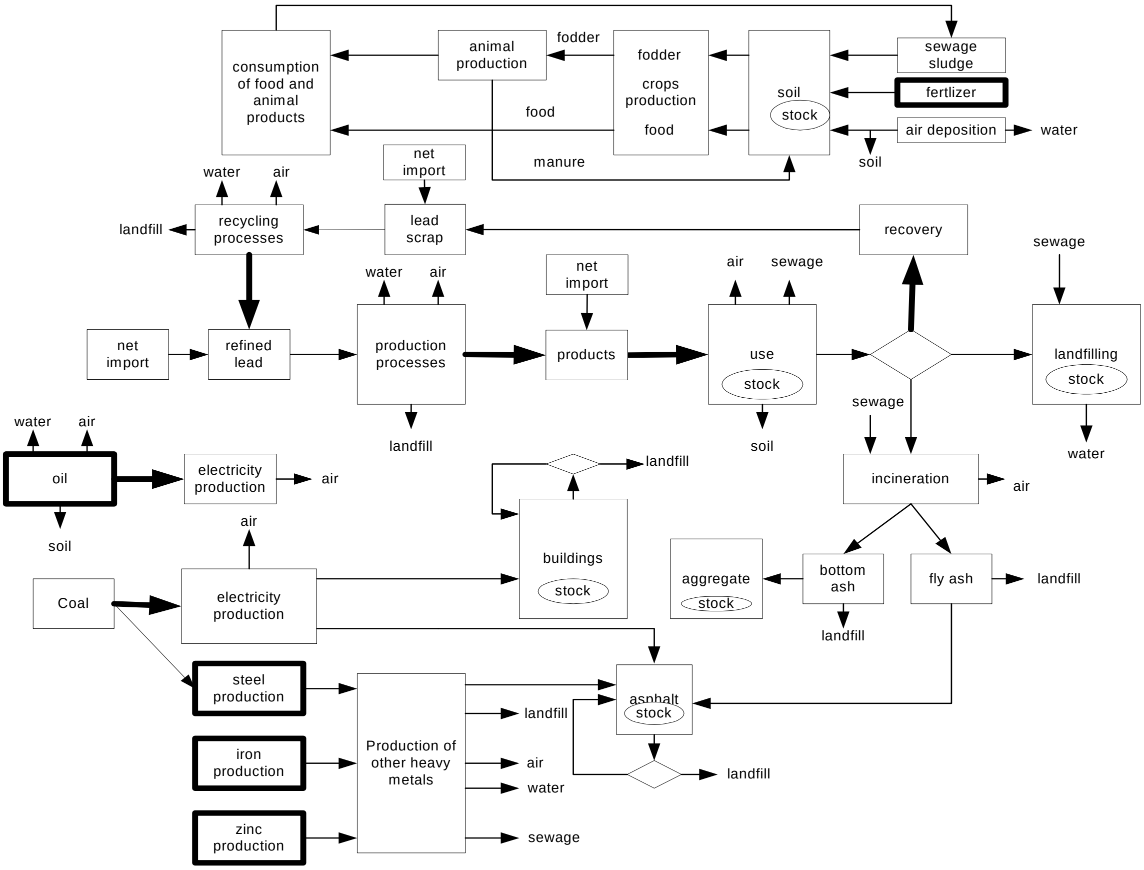

Figure 3: Lead flows and stocks in the economic and part of the environmental systems, the bold lines and boxes mean the flow has a fixed value.

5.2. Production processes

The stock in production processes of lead containing applications is ignored. The processes are connected to several lead flows such as the inflow of refined lead (produced in the region or imported), lead emissions to air, lead emissions to water, the waste flow to landfill and lead flows in the produced products. These flows are shown in figure 4. For some of these flows, time series are available for the past. These can be used to estimate the future flows, either by regression analysis or different scenarios. For other flows, no such information is available. In the model, the available time series will be used as fixed flows for every year. The unknown flows will be estimated either as balancing items through the overall material balance of the production processes, or through the known flows as model relations (formulas).

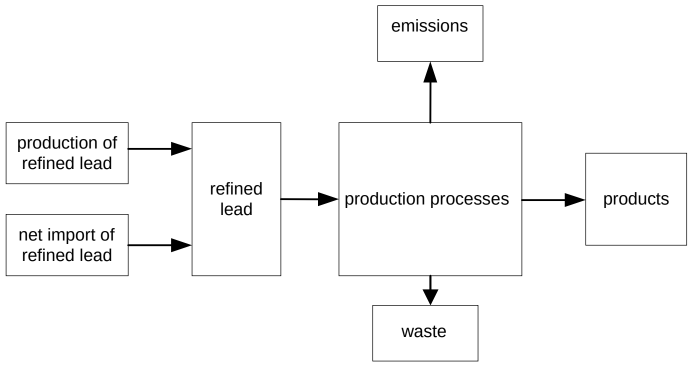

Figure 4: Lead flows connected to the production process

5.2.1. Inflow of lead into the production process

The total inflow of refined lead into the production processes is the amount of refined lead produced in the Netherlands (NL) plus the net import of refined lead. For the production of refined lead in the past, time series are available. The future production of refined lead can be estimated using regression analysis. The future net import, however, is rather difficult to estimate. Therefore, it is difficult to estimate the total inflow of refined lead. Alternatively, the total inflow of refined lead can be estimated from the production processes themselves. The net import of refined lead thus can be estimated as the difference between the total inflow of lead into the production process and refined lead produced in the NL.
The total inflow of refined lead is the sum of the inflows of refined lead into different applications production processes. The modelled lead applications are SLI batteries, industrial batteries, traction batteries, lead sheet, cable sheathings, CRTs, small vehicles applications, ammunition, gasoline and other applications (chemical applications, sound proof applications, food cans, pipes, car radiator and body, optical glass, ceramic, plastic, paint, and others).

The inflow of refined lead into the production process of a certain application is estimated as a balancing item of the production process. It is equal to the outflow of lead in the produced product plus the other lead outflow from the production process (air emissions).

5.2.2. Outflow of lead from the production process

The outflow of lead from the production process is the amount of lead in the product and lead emissions into air during the production processes.

5.2.2.1. Lead outflow in products

Time series of the past outflow of lead in products such as batteries, lead sheet, cable sheathing, and CRT's are available. This can be used to estimate the future lead outflow in products by regression analysis or scenarios. This flow will be treated in the model as a fixed flow.

For ammunition no such time series were available due to confidentiality reasons. The past outflow of lead in produced ammunition is therefore estimated as a fraction of the total past lead outflow in all other applications. For the future, different scenarios can be used.

5.2.2.2. Lead emissions to air

Lead emissions to air from the production of a certain application are estimated as a fraction of the amount of lead in the produced products.

5.2.2.3. Lead emissions to water

Lead emissions to water from the production of a certain application are estimated as a fraction of the amount of lead in the produced products.

5.2.2.4. Lead in the waste stream

Lead in the waste stream from the production of a certain application is estimated as a fraction of the amount of lead in the produced products.

5.2.3. Net import of refined lead

By knowing the total inflow of lead to the production processes and the refined lead produced in the NL, the net import of refined lead can be estimated as a balancing item.

5.3. Use phase

The use phase includes two types of lead applications, stock-building applications (applications with a life span of more than one year) such as batteries, lead sheet, cable sheathings, CRT's, and small vehicle applications and short-living applications (applications with a life span of one year and less) such as ammunition, gasoline and others. Other applications such as chemical applications, sound proof applications, food cans, pipes, car radiator and body, optical glass, ceramic, plastic, paint, and others are not included in the use phase sub-model.

The use phase of stock-building applications is connected to several flows and stocks such as the inflow of lead through different applications, lead emissions during use, the discarded waste stream of lead containing products and the lead applications stock-in-use as shown in figure 5. One of these flows, namely, the inflow of lead through different products is known and can be estimated for the future using regression analysis. In the model, this flow will be treated as a fixed flow. Other flows such as lead emissions during use and the discarded flow will be estimated as model relations. The stock is determined by the inflow of lead through different products and the outflow of lead by the two mechanisms of leaching and delay, as described already in the report on the dynamic stock model.

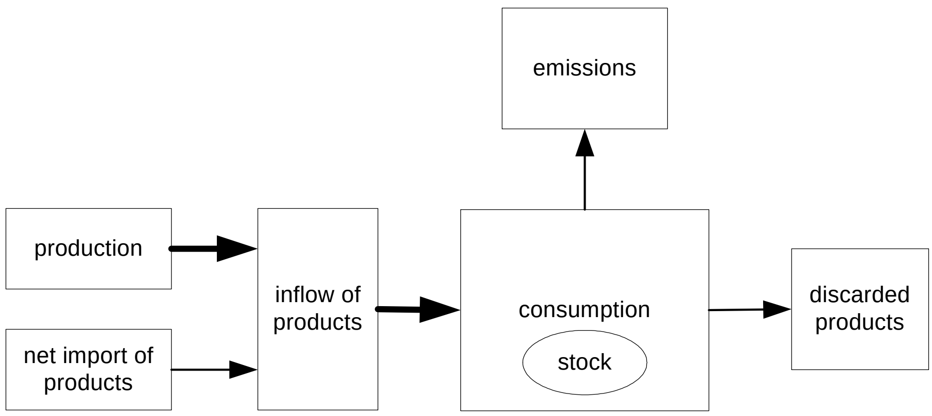

Figure 5: Lead flows and stocks connected to use phase

5.3.1. Inflow of lead into the use phase

Time series of the past inflow of lead through different products, whether these are stock-building applications or short-living applications, are available. This can be used to estimate the future inflow by regression analysis.

5.3.2. Outflow of lead from the use phase

The outflow of lead from the use phase of the two types of applications is lead emissions during use and the discarded waste stream of lead containing products.

5.3.2.1. Discarded waste stream of lead containing products

The discarded waste stream of stock-building applications is estimated as the inflow of lead, with a delay equal to the product life span, minus lead emissions from the inflow during the product life time.
The discarded waste stream of short-living applications is estimated as the inflow of lead without delay (i.e. at the same year) minus lead emissions from the inflow during use (one year).

5.3.2.2. Emissions during use

For some applications such as SLI batteries, traction batteries, industrial batteries, CRT’s, and small vehicle applications, there are no emissions during use. For other applications such as lead sheet, cable sheathing, gasoline and ammunition, emissions during use do occur.
The emissions during use for stock-building applications are estimated as a fraction of the stock. For short-living applications, the emissions during use are estimated as a fraction of the inflow.

5.3.2.2.1 Lead sheet in buildings

Lead emissions during the use phase of lead sheet in buildings will end up in sewage treatment and soil. Both are estimated as a fraction of the total lead emissions from lead sheet in buildings.

5.3.2.2.2 Cable sheathing

Lead emissions during the use phase of cable sheathing will end up in soil.

5.3.2.2.3 Gasoline

Lead emissions during the use phase of gasoline will end up in air and are estimated as a balancing item.

5.3.2.2.4 Ammunition

The outflow of ammunition will either be collected or end up in soil. 50% of the used ammunition is assumed to be emitted to the soil (agricultural and non-agricultural soil).

5.3.3. Net import of different products

The net import of products is the difference between the inflow of lead through different products into use and the amount of lead in produced products in the NL. The inflow of lead through different products and the inflow of lead through the produced products in the NL are known. The net import thus can be estimated.

5.4. Waste management

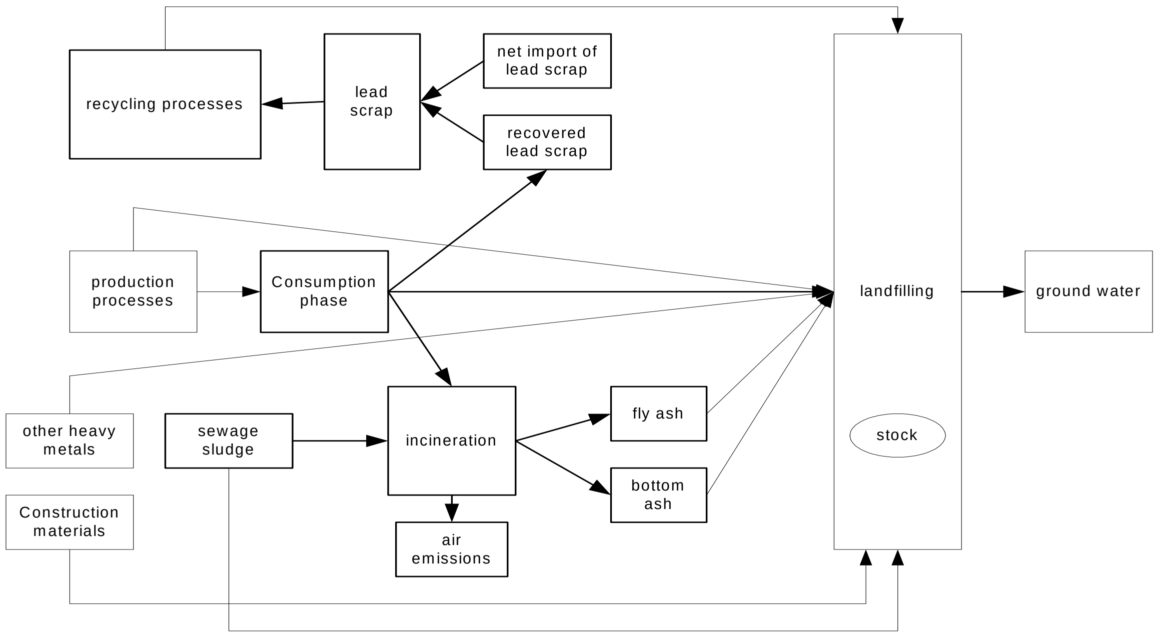

Figure 6: Lead flows and stocks in the waste management phase

5.4.1. Collection

Collection of the waste stream of lead containing products is a stage connected to several flows of lead such as the collected waste stream of lead containing products discarded from the use phase, net import of waste stream of lead containing products and the waste stream of industrial production processes in the region.

5.4.1.1. Collected waste stream of lead containing products

The past and future collected waste stream from the discarded products is estimated as a fraction of the total past and future discarded waste stream from the use phase. The total discarded waste stream from the use phase is estimated before (see the use phase). The collection rate is changing over time. Therefore, it can be estimated either by regression analysis or it can be left as a parameter to be adjusted in a scenario.

5.4.1.2. Processed waste stream in the region

The processed waste stream in the NL can be estimated from the collected waste stream and the net import of lead scrap. Although it is possible to find data on the past and future collected waste streams, the future net import of lead scrap is rather difficult to estimate. Alternatively, the processed flow in the region can be estimated from the recycling processes (see recycling processes).

5.4.1.3. Net import of lead scrap

The net import of lead scrap is the difference between the processed waste stream in the region and the collected waste stream from the discarded products. (see recycling processes)

5.4.2. Incineration process

The incineration process is connected to several flows of lead. Some of these flows are known or estimated in other parts of the model such as the inflow of lead to the incineration plants from the waste stream of lead containing products discarded from the use phase, and the inflow of lead from sewage sludge. Other flows will be estimated as model relations such as the outflow of lead in the incineration residues (fly ash and bottom ash) and lead emissions into air.

5.4.2.1. Inflow of lead into the incineration

The inflow of lead into the incineration plants originates from two sources:

5.4.2.1.1 Waste stream of lead containing products discarded from the use phase

The inflow of lead into the incineration plants from the waste stream of lead containing products discarded from the consumption phase is estimated together with the waste flow to-be-landfilled. The waste flow to incineration and the waste flow to landfill, together are estimated as the difference between the total discarded waste stream and the collected waste stream. The total discarded waste stream is estimated in the use phase (see the use phase) and the collected waste flow is estimated in the collection phase (see the collection phase). The incinerated flow thus is estimated as a fraction of the total not-collected flow.

5.4.2.1.2 Lead in Sewage sludge

The inflow of lead into the incineration plants from sewage treatment is estimated as a fraction of the total amount of lead in the sewage sludge (see sewage treatment).

5.4.2.2. Outflow of lead from the incineration

The incineration process has three outflows: fly ash, bottom ash and emissions to air. All of those outflows contain lead. The outflows of lead from the incineration plants in bottom ash, fly ash and air emissions are each estimated as a fraction of the total inflow of lead to the incineration plants.

5.4.3. Landfilling

On landfill sites, stock-building of lead takes place. The change of the magnitude of the lead stock in landfill sites is determined by the inflow of lead into the stock from different sources, and the outflow of lead from the stock through the leakage to the ground water.

5.4.3.1. Inflow of lead into landfill sites.

5.4.3.1.1 Waste stream from production processes

The inflow of lead into the landfill sites from the production processes is estimated as a fraction of the amount of lead in the produced products (see production processes).

5.4.3.1.2 Waste stream of lead containing products discarded from the use phase

The inflow of lead into the landfill sites from the waste stream discarded from the use phase is estimated together with the waste flow to-be-incinerated. The waste flow to incineration and the waste flow to landfill together are estimated as the difference between the total discarded waste stream and the collected waste stream. The total discarded waste stream is estimated in the use phase (see the use phase) and the collected waste stream is estimated in the collection phase (see the collection phase). The landfilled flow thus is estimated as a fraction of the total not-collected waste flow.

5.4.3.1.3 Waste stream from the recycling processes

The inflow of lead into the landfill sites from the recycling processes is estimated as a fraction of the produced refined lead (see recycling processes)

5.4.3.1.4 Bottom ash and fly ash

The inflows of lead from bottom ash and fly ash are estimated as balancing items of the use of aggregate and asphalt (see bottom ash and fly ash)

5.4.3.1.5 Sewage sludge

The inflow of lead from sewage treatment is estimated as balancing item of the sewage treatment process (see sewage treatment)

5.4.3.1.6 Construction materials

The inflow of lead from construction materials is estimated as a fraction of the construction materials discarded waste stream (see construction materials).

5.4.3.1.7 Production of other heavy metals

The inflow of lead from the production of other heavy metals is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production (see production of other heavy metals).

5.4.3.2. Outflow of lead from landfill sites

The outflow of lead from landfill sites takes place through the leakage of lead to water, which can be estimated as a fraction of the stock.

5.5. Recycling processes

The recycling processes within the region are connected to several lead flows. The inflow is determined by the waste stream of lead containing products, which is the collected waste stream from the discarded products plus the net import of the waste stream of lead containing products. The outflows of the process are the produced refined lead, lead emissions into air and water and lead containing waste ending up in the landfill sites. These flows are shown in figure 7. Although the past and future collected waste streams from the discarded products can be specified, it is difficult to estimate the inflow into the recycling processes due to the difficulties in the future estimates of the net import of waste stream. Alternatively, the inflow of waste stream to the recycling processes can be estimated through the material balance of the recycling processes and then the net import can be estimated.

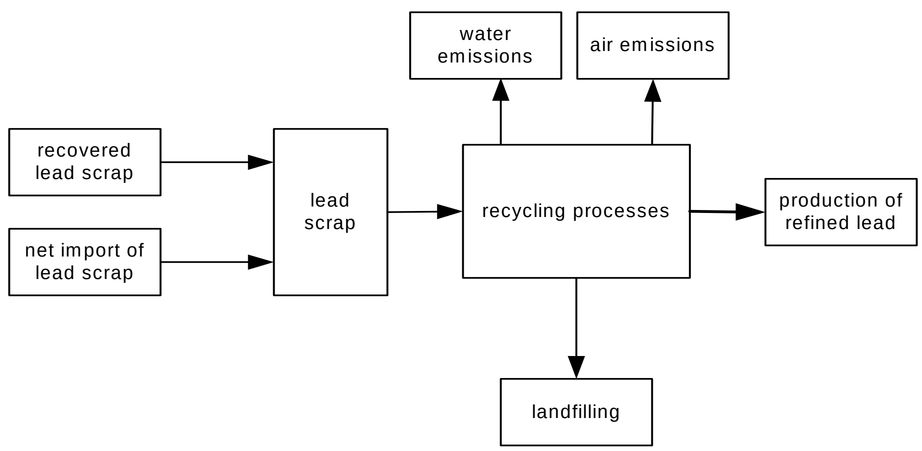

Figure 7: Lead flows connected to the recycling processes

5.5.1. Inflow of waste stream of lead containing products into the recycling processes

The inflow of waste stream of lead containing products into the recycling processes is estimated as a balancing item of the recycling processes. It is equal to the produced refined lead plus other outflows from the recycling processes (air emissions, water emissions and waste flow).

5.5.2. Outflow of lead from recycling processes

The outflow of lead from the recycling processes is the produced refined lead, lead emissions into air and water and the lead waste flow to landfill sites.

5.5.2.1. Produced refined lead

Time series of the past production of refined lead are available. This can be used to estimate the future production of refined lead by regression analysis. The produced refined lead will be treated in the model as a fixed flow.

5.5.2.2. Lead emissions into air

Lead emissions into air during recycling processes are estimated as a fraction of the produced refined lead.

5.5.2.3. Lead emissions into water

Lead emissions into water during recycling processes are estimated as a fraction of the produced refined lead.

5.5.2.4. Lead in the waste stream

Lead in the discarded waste stream from the recycling processes is estimated as a fraction of the produced refined lead.

5.5.3. Net import of waste stream of lead containing products

By knowing the inflow of waste stream of lead containing products to the recycling processes and the collected waste stream from the discarded products, the net import of waste stream can be estimated.

5.6. Bottom and fly ash

5.6.1. Inflows of lead into bottom ash and fly ash

The inflows of lead into the bottom ash and fly ash are estimated in the incineration process as fractions of the total inflow of lead into the incineration plants (see incineration process).

5.6.2. Outflow of lead from bottom ash and fly ash

Bottom and fly ash either is used in road construction materials, or ends up in landfills.

- The outflows of both lead in the utilized bottom ash in aggregate and fly ash in asphalt are estimated as a fraction of the inflow of lead into the bottom ash.
- The outflow of lead to landfill sites is estimated as a balancing item (the difference between the inflow of lead and the outflow of lead in the utilized bottom and fly ash).

5.7. Sewage treatment

Sewage treatment is a stage connected to several lead flows. Its inflows come from the emissions during use, from the consumption of food and animal products and from industrial processes, especially the production of other heavy metals. Its outflows are effluent and sewage sludge. Part of the inflow of lead will end up in the sewage sludge and the remaining amount of lead will end up in the effluent. The sludge is distributed over soil (use as fertilizer or soil improvement material), incineration, landfill and other destinations.

5.7.1. Inflow of lead into sewage treatment

5.7.1.1. Emissions during use

The inflow of lead into the sewage treatment from the use phase is estimated as a fraction of the total lead emissions during the use phase of lead sheet (see use phase). Other lead applications are assumed not to leach into the sewage system.

5.7.1.2. Consumption of food and animal products

The inflow of lead into the sewage treatment from the consumption of food and animal products is estimated as a balancing item in the consumption of food and animal products (see consumption of food and animal products).

5.7.1.3. Production of other heavy metals

The inflow of lead into the sewage treatment from the production of other heavy metals is estimated as a fraction of the total inflow of lead to the production of other heavy metals through zinc, iron and coal used for steel production (see production of other heavy metals).

5.7.2. Outflow of lead from sewage treatment

- The outflow of lead from sewage treatment ends up in sewage sludge and in the effluent. The outflow of lead in sewage sludge is estimated as fraction of the inflow. The amount of lead in the effluent is estimated as a balancing item of the waste treatment process
- The outflows of lead in sewage sludge to soil, to waste incineration and to other destinations are estimated as fractions of the total outflow of lead in the sewage sludge.
- The outflow of lead in sewage sludge to landfill sites is estimated as a balancing item of the sewage sludge.

5.8. Construction materials

Lead ends up in construction materials through the recycling of waste materials such as ashes and slag. Construction materials are therefore non-intentional stock-building applications of lead. The lead stock in construction materials is connected to several flows of lead such as the inflow of lead from bottom and fly ash from waste incineration, industrial processes and electricity production. The change of the magnitude of the stock is determined by the inflow of lead through different sources and the outflow of lead through the two mechanisms of leaching and delay.

5.8.1. Inflow of lead into construction materials

5.8.1.1. Bottom and fly ash

The inflow of lead into the stock of roads-in-use from bottom ash and fly ash is the utilized flow of both in aggregate and asphalt and estimated as a fraction of the inflow of lead into bottom and fly ash (see bottom and fly ash).

5.8.1.2. Production of other heavy metals

The inflow of lead into the stock of roads-in-use from the production of other heavy metals is the utilized flow in asphalt and estimated as a fraction of the total inflow of lead from zinc, iron and steel production (see production of other heavy metals).

5.8.1.3. Electricity production from coal

The inflow of lead into the asphalt from coal used in electricity production is estimated as a fraction of the total inflow of lead through coal (see electricity production from coal).

5.8.1.4. Electricity production from coal

The inflow of lead into the buildings from coal used in electricity production is estimated as a balancing item in electricity production (the difference between the total inflow of lead through coal and lead emissions into air plus the amount of lead utilized in asphalt) (see electricity production from coal)

5.8.2. Outflow of lead from construction materials

The stock of construction materials-in-use theoretically has three outflows of lead through the delay mechanism, and two outflows of lead through the leaching mechanism. The outflows through the delay mechanism are related to asphalt, road aggregate, and buildings. The outflows through the leaching mechanism are related to the leakage of lead from road materials to the soil and the leaching of lead from building materials. Leaching may occur as a result of processes in the soil, which may free the lead out of the road materials. It is uncertain whether this happens, and if so, to what extent. In most studies this flow is ignored. Due to lack of data, we also will ignore this flow. The same in the case of building material, due to the lack of data, the leaching flow will be ignored.

5.8.2.1. Discarded outflow related to asphalt

Discarded outflow of lead from asphalt is estimated as the total inflow of lead to asphalt from fly ash and the production of other heavy metals with a delay equal to the life span of the top layer of the road.

5.8.2.2. Discarded outflow related to road aggregate

The assumption is made that the aggregate is not replaced but stays in place as long as the road does.

5.8.2.3. Discarded outflow related to buildings

Discarded outflow of lead from buildings is estimated as the total inflow of lead to buildings from electricity production with a delay equal to the buildings life span.
The discarded outflows from asphalt and buildings are either landfilled or recycled.
Both the flow of lead ending up in landfill sites and the flow of lead that will be recycled are estimated as fractions of the total discarded outflow from both asphalt and buildings.

5.9. Production of other heavy metals

The production of other heavy metals is connected to several lead flows due to the fact that lead occurs as a contaminant in the ores of these metals. This process is, for practical reasons, defined as an aggregate process. In fact the production of zinc, iron and steel each have their own dynamics. Inflows of this aggregate process are lead in zinc, in iron, and in coal used for steel production. Lead outflows are waste flows and emissions: to construction materials, to landfill sites, to sewage treatment, and lead emissions into air and water. Some of these flows are known for the past and can be estimated for the future. Others will be estimated as model relations.

5.9.1. Inflow of lead into the production of other heavy metals

5.9.1.1. Zinc, iron and steel production

The past and future inflow of lead through zinc and iron and coal used for steel production is estimated on the basis of the past and future refined zinc, iron and steel produced in the NL. Time series of the past production of refined zinc, iron and steel are available. These can be used to estimate the future production of zinc, iron and steel by regression analysis. These flows will be treated as fixed flows in the model.

5.9.2. Outflow of lead from the production of other heavy metals

5.9.2.1. Lead in construction materials (asphalt)

The outflow of lead from the production of other heavy metals to construction material (asphalt) is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production.

5.9.2.2. Lead in the waste stream

Lead in the discarded waste stream from the production of other heavy metals is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production.

5.9.2.3. Lead emissions to air

Lead emissions to air from the production of other heavy metals is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production.

5.9.2.4. Lead emissions to surface water

Lead emissions to water from the production of other heavy metals is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production.

5.9.2.5. Lead in Sewage sludge

The outflow of lead from the production of other heavy metals to the sewage treatment is estimated as a fraction of the total inflow of lead through zinc, iron and coal used for steel production.

5.10. Electricity production from coal

Electricity production from coal is a process connected to three lead flows. The inflow of lead through coal used in electricity production, lead emissions into air and the outflow of lead utilized in buildings. The past inflow is known and can be estimated for the future. The two outflows will be estimated as a model relation.

5.10.1. Inflow of lead into electricity production from coal

The past and future inflow of lead through coal used in electricity production is estimated on the basis of the past and future coal used in electricity production. Time series of the past flow of coal used in electricity production are available. These can be used to estimate the future flow of coal used in electricity production by regression analysis. This flow will be treated as a fixed flow in the model.

5.10.2. Outflow of lead from electricity production from coal

5.10.2.1. Lead emissions to air

Lead emissions to air during electricity production are estimated as a fraction of the total inflow of lead through coal.

5.10.2.2. Lead utilized in asphalt

Most of the lead in the coal fueling process ends up in fly ash. This fly ash is partly utilized in asphalt. The outflow of lead to asphalt is estimated as a fraction of the total inflow of lead through coal.

5.10.2.3. Lead in fly ash utilized in buildings

Most of the lead in the coal fueling process ends up in fly ash. This fly ash is partly used in construction materials such as cement and concrete. The outflow of lead to buildings is estimated as a balancing item (the difference between the inflow of lead through coal and the emitted outflow plus the utilized flow in asphalt)

5.11. Oil production

5.11.1. Refined oil production

Lead is a contaminant in crude oil and therefore passes through the oil refinery process. Time series of the past refined oil production are available. This can be used to estimate the future production of refined oil by regression analysis. This flow will be treated as a fixed flow in the model.

5.11.2. Outflow of lead from oil production

5.11.2.1. Lead emissions to air, water and soil

Lead emissions to air, water and soil during the oil production process are estimated as a fraction of the produced refined oil.

5.12. Electricity production from oil

This case is treated similarly to the above electricity production from coal (section 5.10)

5.12.1. Inflow of lead into electricity production from oil

The past and future inflow of lead through oil used in electricity production is estimated on the basis of the past and future oil used in electricity production. Time series of the past flow of oil used for electricity production are available. These can be used to estimate the future flow of oil used for electricity production by regression analysis. This flow will be treated as a fixed flow in the model.

5.12.2. Outflow of lead from electricity production from oil

The outflow of lead from electricity production from oil is lead emissions to air and is estimated on the basis of the electricity produced from oil.

5.13. Agricultural sector

In agricultural soil, stock building of lead takes place. The change of the magnitude of the lead stock in the soil over time is determined by the inflow of lead into soil through different sources and the outflow of lead from it. The inflow of lead into the agricultural soil originates from different sources such as fertilizers, sewage sludge, manure and lead deposited from air. The outflows of lead from the agricultural soil are the amount of lead taken up by the food and fodder crops. These flows are further contributing to the lead stock in soil through loops in the system, especially related to animal production (manure) and food products (sewage sludge). Flows and stocks connected to the agricultural soil are shown in figure 8.

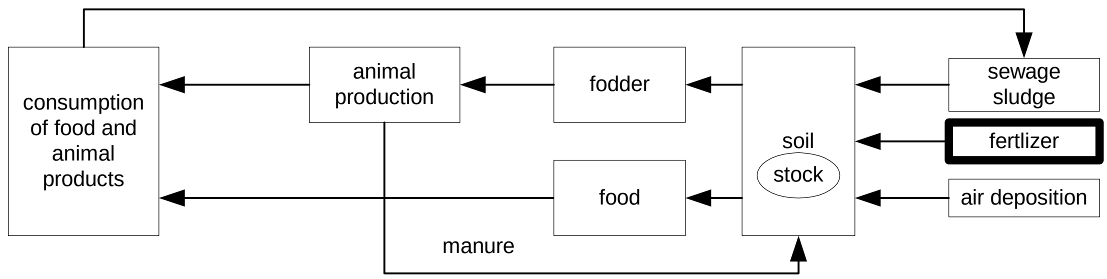

Figure 8: Lead flows and stocks connected to the agricultural soil.

5.13.1. Agricultural soil

5.13.1.1.Inflow of lead into the agricultural soil

The inflow of lead into the agricultural soil originates from different sources:

5.13.1.1.1 Fertilizers

Lead occurs in phosphate fertilizer as a contaminant. The past and future inflow of lead into the agricultural soil due to the use of fertilizers is estimated on the basis of the inflow of fertilizer and an assumption about the lead content in the fertilizer. Time series of the past inflow of fertilizers are available. This can be used to estimate the future inflow of fertilizers by regression analysis. This flow will be treated as a fixed flow in the model.

5.13.1.1.2 Sewage sludge

The inflow of lead into the agricultural soil through sewage sludge is one of the outflows from the sewage treatment process (see sewage treatment). The flow is estimated as a fraction of the total inflow of lead into the sewage treatment. The inflow of lead into the sewage treatment, however, is not completely known due to the presence of loops within the agricultural sector. The inflow is partly influenced by the outflow of lead from the consumption of food and animal products. This flow will remain unknown and will be estimated as a balancing item of the food and animal product consumption process.

5.13.1.1.3 Air deposition

The deposited flow of lead from air into the agricultural soil originates from different sources of the economic system (production, consumption, recycling and incinerating of lead applications, the use of fossil fuel in electricity production, and the production of other heavy metals containing lead). The deposition flow is estimated as a fraction of the total lead emitted flow to air (see air).

5.13.1.1.4 Manure

The lead inflow into the agricultural soil due to the use of manure is estimated as a balancing item of the animal production process (see animal production).

5.13.1.1.5 Ammunition

The lead inflow into the agricultural soil due to the use of ammunition is estimated as a fraction of the non-collected ammunition after use (see use phase).

5.13.1.2. Outflow of lead from the agricultural soil

5.13.1.2.1 Fodder and food crops

The quantity of lead from the agricultural soil, which is taken up by the fodder and food crops, is estimated as a fraction of the stock of lead in the agricultural soil

5.13.2. Crop production

The inflow of lead into crop production is the outflow of the agricultural soil to fodder and food crops. These flows are estimated as a fraction of the lead stock in the agricultural soil (see agricultural soil).
The outflows of lead from crop production are the flow of lead through fodder to animal production and the flow of lead through food crops to the consumption of food and animal products. Both are estimated as balancing items.

5.13.3. Animal production

The inflow of lead into animal production through fodder is estimated as a balancing item in crop production (see crop production).

Two outflows are connected to animal production. One of them is the outflow to the consumption of food and animal products and the other one is the outflow to soil (manure).
The outflow to the consumption of food and animal products is estimated as a fraction of the lead inflow.
The outflow to soil (manure) is estimated as a balancing item (the difference between the inflow of lead and the outflow of lead to the consumption processes)

5.13.4. Consumption of food and animal products

The inflow of lead into the consumption processes originates from two sources: animal production and crop production through food crops. The inflow of lead from animal production is estimated as a fraction of the lead inflow to the animal production (see animal production).
The inflow of lead from crop production through food crops is estimated as a balancing item in crop production (see crop production).
The outflow of lead from the consumption processes to sewage treatment is estimated as a balancing item (the total inflow).

5.14. Environmental flows and stocks

Lead flows and stocks in the environmental compartments (air, water and soil) originate from lead economic activities (production, consumption, and waste management) whether these activities are related to the intentional use of lead or its non-intentional use. Lead flows and stocks in the environment are also connected to each other, leading to flows from one environmental compartment to another.

5.14.1. Air

5.14.1.1. Inflow of lead into air

Lead inflow into air originates from different sources. Some of these sources are related to the intentional use of lead and others to its non-intentional use.

5.14.1.1.1 Production of different lead applications

The inflow of lead into air from the production of different lead applications is estimated as a fraction of the amount of lead in the produced products (see production processes).

5.14.1.1.2 Use of different lead applications

The inflow of lead into air from the use phase of lead applications originates from the use of leaded gasoline which is phased out in the NL. The past emissions of lead to air from the use of gasoline are estimated as a fraction of the total lead present in gasoline (See use phase).

5.14.1.1.3 Recycling processes

The inflow of lead into air from recycling processes is estimated as a fraction of the produced refined lead (see recycling processes).

5.14.1.1.4 Incineration process

The inflow of lead into air from the incineration plants is estimated as a fraction of the total inflow of lead to the incineration plants (see incineration process).

5.14.1.1.5 Electricity production from coal

The inflow of lead into air from coal used in the production of electricity is estimated as a fraction of the inflow of lead through the used coal (see electricity production from coal).

5.14.1.1.6 Electricity production from oil

The inflow of lead into air from oil used in the production of electricity is estimated as a balancing item (the inflow of lead through oil) (see electricity production from oil).

5.14.1.1.7 Production of other heavy metals

The inflow of lead into air from the production of other heavy metals is estimated as a fraction of the total inflow of lead through iron, zinc and coal used in steel production (see production of other heavy metals).

5.14.1.1.8 Production of oil

The inflow of lead into air from the production of oil is estimated as a fraction of the inflow of lead through oil (see oil production).

5.14.1.2. Outflow of lead from the air

The outflow of lead from air is the amount of lead deposited in water, soil (agricultural and non-agricultural) and outside the region.

5.14.1.2.1 Lead deposited in soil (agricultural and non-agricultural)

The outflow of lead from air to the agricultural and non-agricultural soil is estimated as a fraction of the total inflow of lead to the air. This fraction is determined by the percentage of the area, which is occupied by soil.

5.14.1.2.2 Lead deposited in water

The outflow of lead from air to water is estimated as a fraction of the total inflow of lead to the air. This fraction is determined by the percentage of the area, which is occupied by water.

5.14.1.2.3 Transboundary flows of lead through air

The amount of lead deposited in the NL and originating from outside the NL does not differ greatly from the amount of lead deposited outside the NL and originating from the NL. Also, transboundary in- and outflows are small compared to the emissions taking place within the Netherlands. Therefore, both transboundary inflow and outflow of lead through air are ignored.

5.14.2. Water

5.14.2.1.Inflow of lead into water

Lead inflow into water originates from different sources. Some of these sources are related to the intentional use of lead and others to its non-intentional use.

5.14.2.1.1 Recycling processes

The inflow of lead into water from recycling processes is estimated as a fraction of the produced refined lead (see recycling processes)

5.14.2.1.2 Production of different lead applications

The inflow of lead into water from the production of different lead applications is estimated as a fraction of the amount of lead in the produced products (see production processes).

5.14.2.1.3 Production of other heavy metals

The inflow of lead into water from the production of other heavy metals is estimated as a fraction of the total inflow of lead through iron, zinc and coal used in steel production (see production of other heavy metals).

5.14.2.1.4 Production of oil

The inflow of lead into water from the production of oil is estimated as a fraction of the inflow of lead through oil (see oil production).

5.14.2.1.5 Deposition from air

The inflow of lead into water from air is estimated as a fraction of the total inflow of lead to air (see air).

5.14.2.1.6 Landfill sites

The inflow of lead into water from landfill sites is estimated as a fraction of the stock of lead in landfill sites (see landfilling).

5.14.2.1.7 Sewage treatment

The inflow of lead into water from sewage treatment plants is estimated as a balancing item of the sewage treatment processes (see sewage treatment).

5.14.3. Non-agricultural soil

5.14.3.1. Inflow of lead into the non-agricultural soil

Lead inflow to non-agricultural soil originates from different sources. Some of these sources are related to the intentional use of lead and others to its non-intentional use.

5.14.3.1.1 Use of different lead applications

The inflow of lead into non-agricultural soil from the use phase of lead applications mainly originates from the use of lead sheet in buildings, cable sheathing, and ammunition. These flows are estimated as a fraction of the stock in the case of lead sheet and cable sheathing and as a fraction of the inflow in the case of ammunition (see the use phase)

5.14.3.1.2 Construction materials

The inflow of lead into non-agricultural soil from construction materials, if any, is estimated as a fraction of the lead stock in these materials (see construction materials).

5.14.3.1.3 Production of oil

The inflow of lead into non-agricultural soil from the production of oil is estimated as a fraction of the inflow of lead through oil (see oil production).

5.14.3.1.4 Deposition from air

The inflow of lead into non-agricultural soil from air is estimated as a fraction of the total inflow of lead to air (see air).

6 SPECIFICATION OF MODEL PARAMETERS AND APPLICATION OF THE MODEL FOR LEAD IN THE NETHERLANDS.

6.1. Production processes of different lead applications

Lead is used in the production process of different applications such as SLI batteries, industrial batteries, traction batteries, lead sheet, cable sheathings, CRTs, small vehicles applications, ammunition, gasoline and other applications (chemical applications, sound proof applications, food cans, pipes, car radiator and body, optical glass, ceramic, plastic, paint, and others).
In the following section the amount of lead in the produced products, the emissions during the production processes and the inflow of lead to the production processes will be estimated.

6.1.1. The outflow of lead from the production processes

The outflow of lead from the production process is the amount of lead in the product and lead emissions to air. The other outflows, lead emissions to the water and lead in the waste stream, are ignored due to the lack of information. These flows are also ignored in other studies.

6.1.1.1. The outflow of lead in the produced lead applications

Time series of the outflow of lead in the past in its different produced applications in the Netherlands (batteries, lead sheet, cable sheathing, CRT's and others) are available. These can be used to estimate the future lead outflow in different applications either by regression analysis as given by Eq.7 or using different scenarios. The future lead outflow in different applications is estimated as given by Eq. 7. To obtain a reliable regression model, the number of observation should cover a certain period of time where the general trend of the development of the flow is stable enough to be explained (for more information on the regression analysis see report 1). Figure 9 and 10 show the outflow of lead in different applications and the total outflow in all applications from 1988 through 1998 (ILZSG, 2000).
The past and future outflow of lead in produced ammunition is estimated as a fraction of the total lead outflow in all applications in the past and the future (because of the lack of time series for ammunition, due to confidentiality reasons).

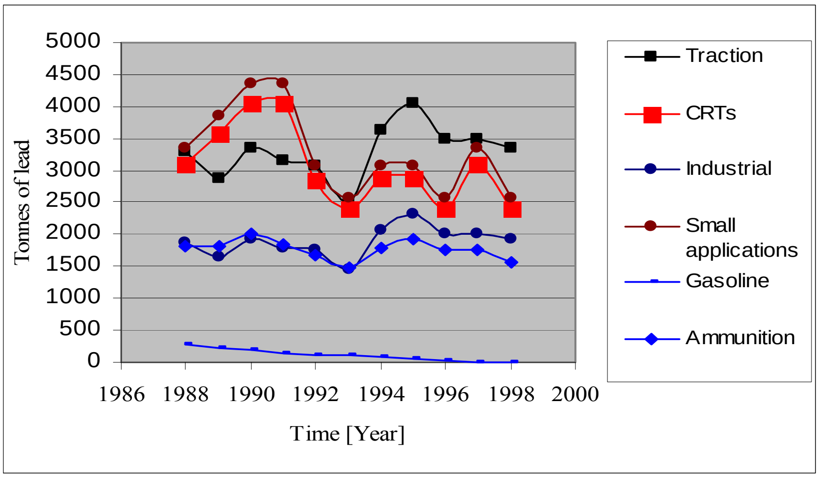

Figure 9: Lead in produced traction batteries, CRTs, industrial batteries, small vehicle applications, gasoline and ammunition in the Dutch economy from 1988 through 1998

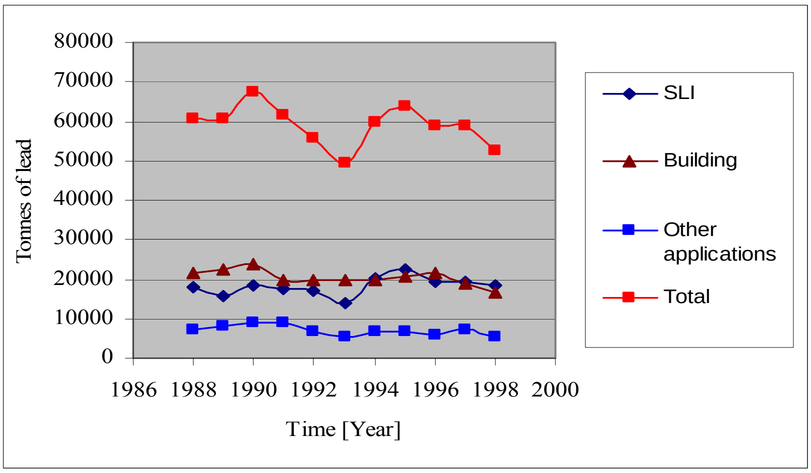

Figure 10: Lead in produced SLI batteries, lead sheet and other applications and the total amount of lead in all produced applications in the Dutch economy from 1988 through 1998

6.1.1.2. Deriving a model equation of the outflow of lead in different applications (1988-1998)

The outflow of lead in the produced lead applications has been tested with different factors such as per capita GDP, and world demand for these applications. The results indicate that the coefficients of determination (R^2) associated with the correlation between the outflow of lead in the produced applications and these factors in most cases are low. Therefore, the time is used as a proxy of the effect of other influential variables on the outflow of lead in these applications to estimate the future (see 7.2 and report 1). The following model equations are used to calculate the future outflow of lead in different applications

The outflow of lead in SLI batteries

$$F^{out}_{P,SLI} = 16464 + 283.5 * time \quad (58)$$

The outflow of lead in traction batteries

$$F^{out}_{P,trac} = 2993 + 51.555 * time \quad (59)$$

The outflow of lead in lead sheet

$$F^{out}_{P,sheet} = 22834 - 402.95*time \quad (60)$$

The outflow of lead in CRTs

$$F^{out}_{P,CRT} = 3759.99 – 116.79*time \quad (61)$$

The outflow of lead in industrial batteries

$$F^{out}_{P,ind} = 1710.5 + 29.45*time \quad (62)$$

The outflow of lead in small vehicles applications

$$F^{out}_{P,SVA} = 4045 – 125.65*time \quad (63)$$

The outflow of lead in other applications

$$F^{out}_{P,OA} = 8494 + 248.89*time \quad (64)$$

The outflow of lead in Gasoline

$$F^{out}_{P,Gas} = 48812 - 24.434*time \quad (65)$$

The outflow of lead in ammunition

The outflow of lead in ammunition is estimated as 3% of the total outflow of lead in all applications. The total outflow in other applications is 97% of the total outflow in all applications. The outflow of lead in ammunitions in terms of the total outflow in other applications is given by equation 66.

$$F^{out}_{P,amm} = (3* total\ outflow)/ 100 \quad (66)$$

$$Total\ outflow\ in\ other\ applications = (79* total\ outflow)/ 100 \quad (67)$$

$$Total\ outflow = (Total\ outflow\ in\ other\ applications *100 / 79 \quad (68)$$

$$F^{out}_{P,amm} = (3* total\ outflow\ in\ other\ applications)/ 97 \quad (69)$$

Using these equations, the outflow of lead in different applications from 1999 onwards is shown in figure 11 and 12.

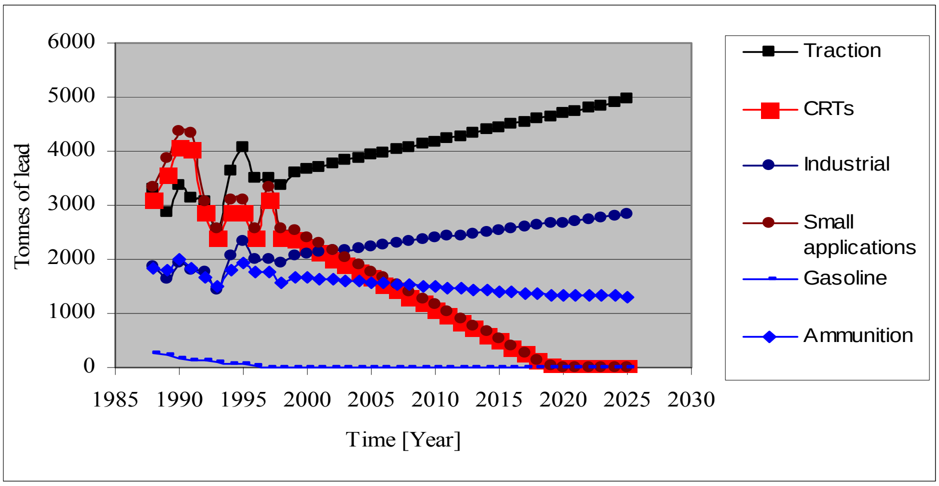

Figure 11: The amount of lead in produced traction batteries, CRTs, industrial batteries, small vehicle applications, gasoline and ammunition in the past and the future

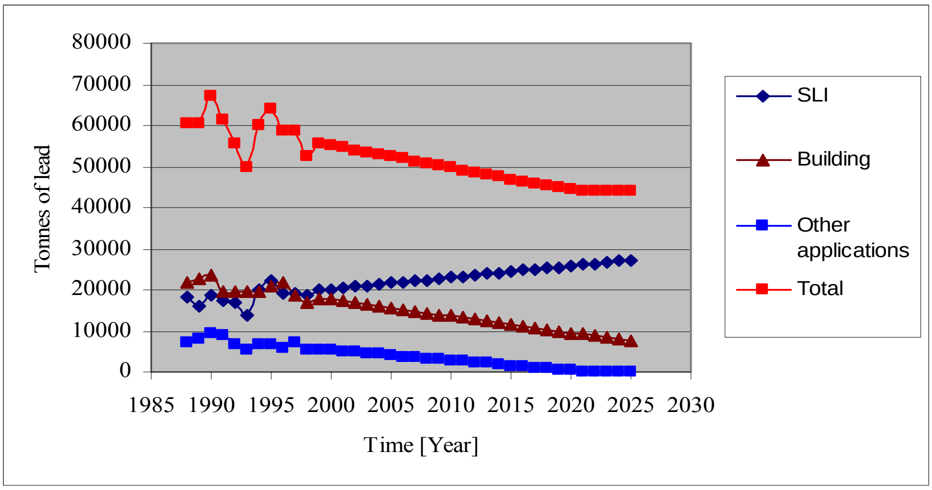

Figure 12: The amount of lead in produced SLI batteries, lead sheet and other applications and the total amount of lead in all produced applications in the past and the future

6.1.1.3. Lead emissions to air during the production process

The amount of lead emitted to air during the production processes of different lead applications is estimated as a fraction of the amount of lead in the produced products as given by Eq. 8, where α_{PE} in Eq. 8 is 0.00084.

The emission factor is estimated as the average value of the total lead emitted to the air from the production processes of different lead applications (EMEP, 2001) divided by the total amount of lead in the produced products for several years in the past (ILZSG, 2000). The same emission factor is used for the future calculations.

Figure 13 and 14 show the amount of lead emitted to air during the production processes of different lead applications in the past and the future.

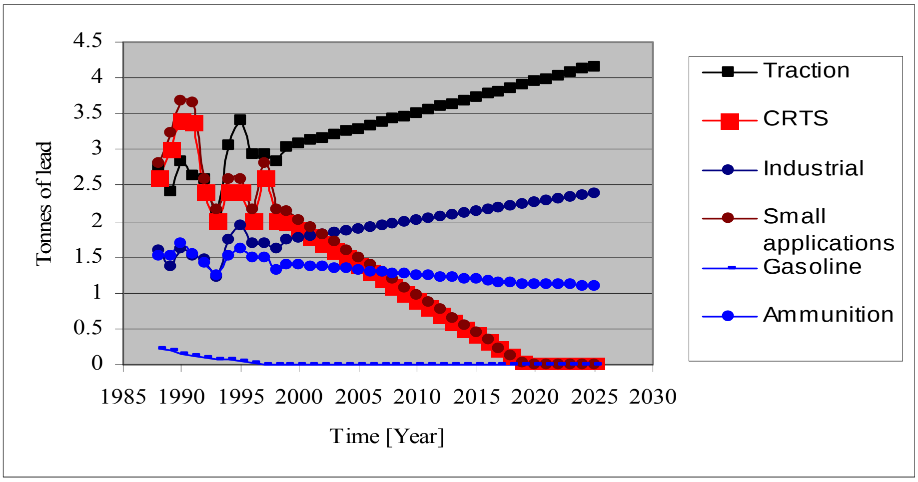

Figure 13: lead emissions during the production processes of traction batteries, CRTs, industrial batteries, small vehicle applications, gasoline and ammunition in the past and the future

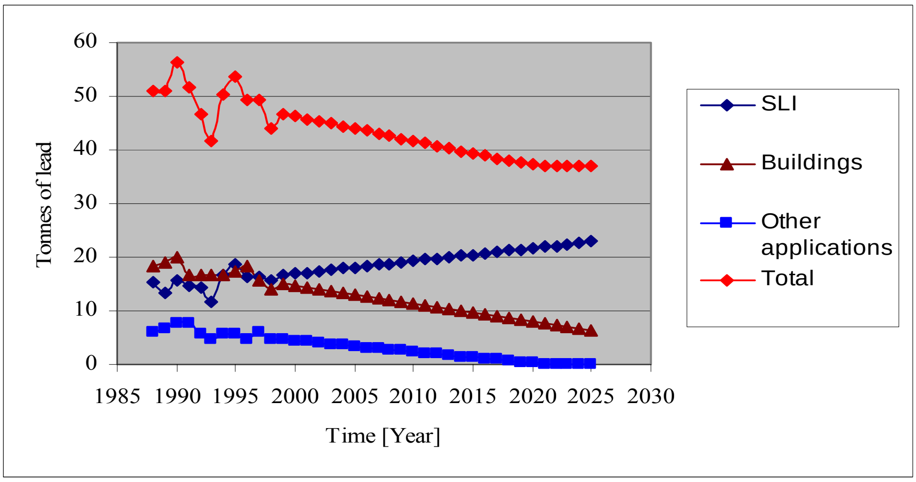

Figure 14: lead emissions during the production processes of SLI batteries, lead sheet and other applications and the total lead emissions in the production of all lead applications in the past and the future

6.1.2. The inflow of lead into the production processes of different lead applications

The inflow of refined lead into the production processes of different lead applications is estimated as a balancing item of the production process as given by Eq. 4. It is the sum of the outflow of lead in the produced product and the emitted lead during the production process to air. Figure 15 and 16 show the inflow of lead into the different applications.

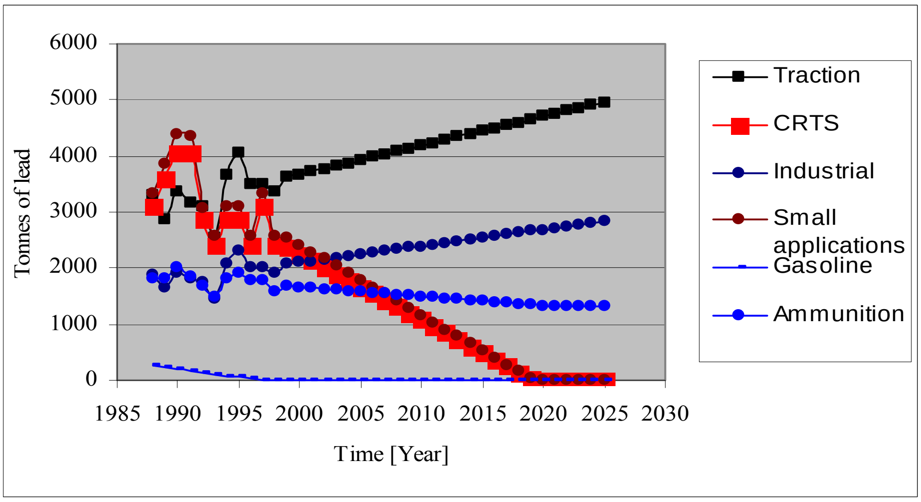

Figure 15: The inflow of lead into the production processes of traction batteries, CRTs, industrial batteries, small vehicle applications, gasoline and ammunition in the past and the future.

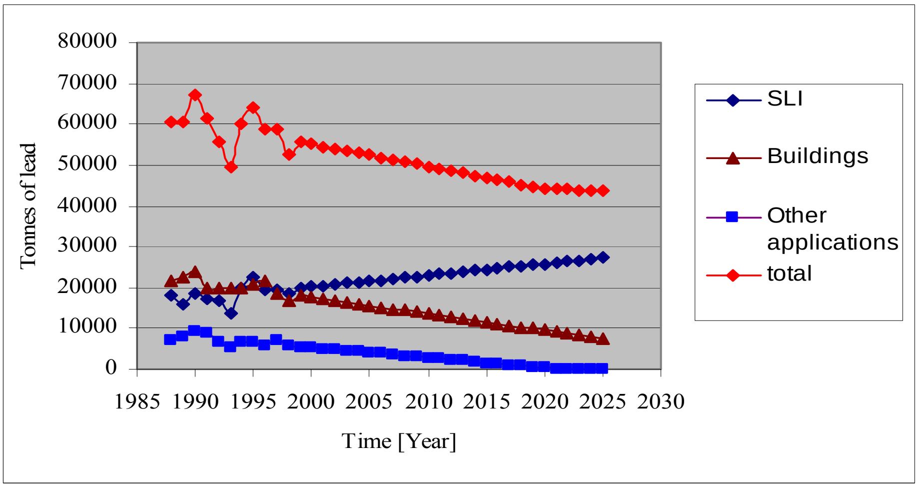

Figure 16: The inflow of lead into the production processes of SLI batteries, lead sheet and other applications and the total lead inflow in the production of all lead applications in the past and the future

6.2. The use phase of different lead applications

6.2.1. Intentional applications of lead

6.2.1.1. Intentional stock-building applications

Stock-building applications are discussed in chapter 6 of the first report - phase 1.

6.2.1.2. Intentional short-living applications

6.2.1.2.1 Inflow of lead into the use phase of short-living applications

Gasoline

The inflow of lead into the use phase of gasoline in the past is the amount of lead in the produced gasoline in the Netherlands plus the imported amount minus the exported amount. Due to the lack of information on import and export of gasoline, the inflow of lead into the use phase will be assumed to be the same as the amount of lead in the produced gasoline in the Netherlands. The future inflow of lead is assumed to be zero due to the phase out policy regarding leaded gasoline. The past and future inflow of lead is shown in figure 17.

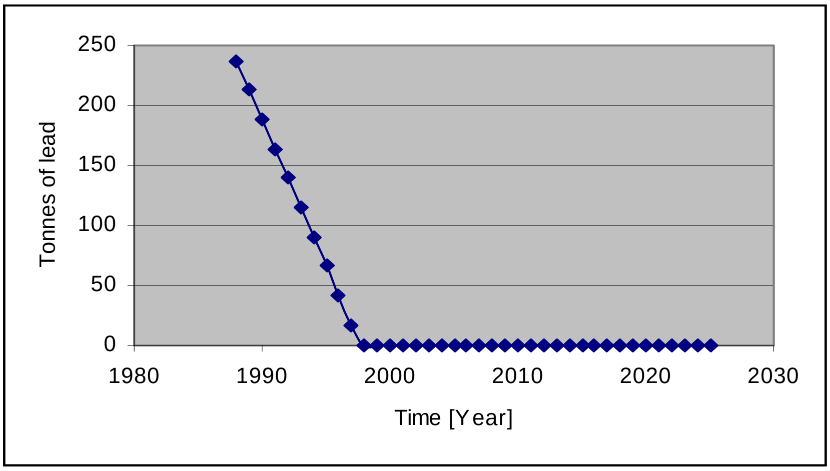

Figure 17: The inflow of gasoline into the use phase of the Dutch economy in the past and the future expressed in tonnes of lead

Ammunition

The inflow of lead into the use phase of ammunition is the amount of lead in the produced ammunition in the Netherlands plus the imported amount minus the exported amount. Due to the lack of information on import and export of ammunition, the inflow of lead into the use phase in the past and the future will be assumed to be the same as the amount of lead in the produced ammunition in the Netherlands in the past and the future (see 6.1.1.1). The past and future inflow of lead in ammunition is shown in figure 18.

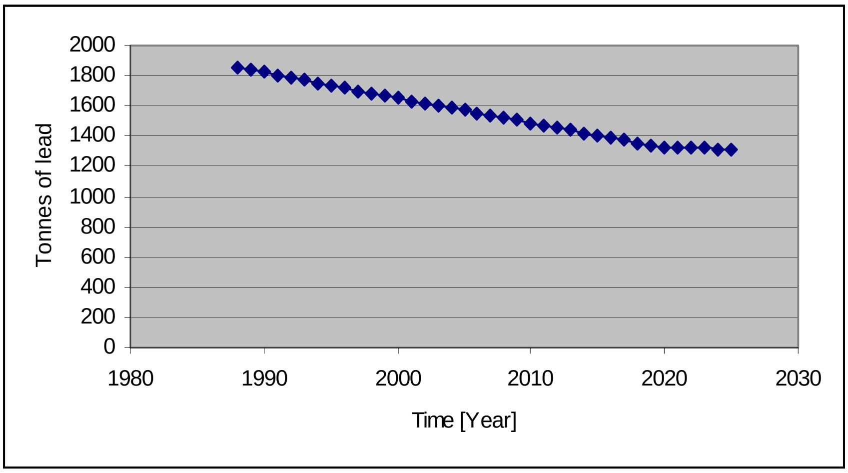

Figure 18: The inflow of ammunition into the use phase of the Dutch economy in the past and the future expressed in tonnes of lead

6.2.1.2.2 Outflow of lead from the use phase

Gasoline Outflow

The outflow of lead from the use phase of gasoline is only the emissions during use, which is equal to the inflow of lead.

Ammunition Outflow

The outflow of lead from the use of ammunition is the collected amount of ammunition and the amount of lead remained in the soil. The amount of lead emitted to the soil is assumed to be 50% of the total outflow. We also assume that 50% of the emitted flow to the soil ends up in agricultural soil and the other 50% in the non-agricultural soil. The outflow is equal to the inflow of lead at the same time. There is no stock during the use phase of ammunition, however, there is a stock in the environment due to the use of ammunition. Figure 19 shows the amount of lead emitted to the soil (agricultural and non-agricultural soil).

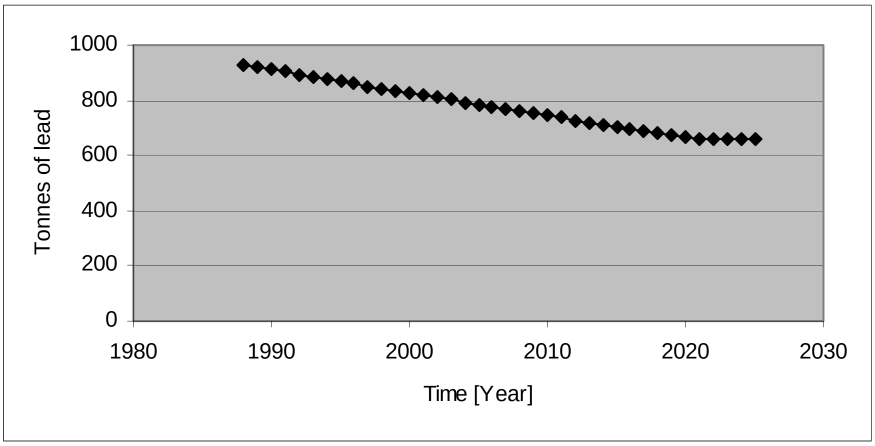

Figure 19: The emitted outflow of ammunition to the soil expressed in tonnes of lead.

6.2.2. Non-intentional applications of lead

6.2.2.1. Non-intentional stock-building applications

6.2.2.1.1 Lead in waste treatment residues

Lead occurs non-intentionally in stock-building applications due to the outflow of its intentional applications especially in the waste management part (recycling and incineration). In the recycling phase of lead applications, slag as an outflow of the recycling processes is used as a road filling, raw material in the manufacturing of cement and filter media for waste treatment plants. Moreover, the incineration residues (fly and bottom ash) are used as materials in road construction (section 6.7 in the first report-phase 1).

6.2.2.1.2 Natural occurrence of lead in ores: Lead in other heavy metals applications

Lead occurs naturally in other heavy metals ores such as bismuth, copper, silver, zinc and iron. As a result, lead exists as a contaminant in these heavy metals' applications. To estimate the amount of lead in the stock of these products, a general model for these substances has to be made. Due to the fact that lead occurs naturally in several heavy metals and these are applied in several applications, it is not possible to make a detailed model for all these substances and their applications. In this case, the inflow of the applications containing these substances will be aggregated on a substance level and modelled on the basis of the socio-economic variables. The lead content can be estimated on the basis of the amount of lead that remains as a contaminant in these heavy metals after the refining processes. The outflow will be determined on the basis of the two mechanisms, leaching and delay. The life span can be assumed either as an average or distributed in time. Weibull distribution can be used to model the life span.

6.2.2.2. Non-intentional short-living applications

6.2.2.2.1 Lead in other heavy metals

Lead occurs naturally in other heavy metals ores such as bismuth, copper, silver, zinc and iron. To estimate the amount of lead that enters the economic system along with these heavy metals, a general model for these substances has to be made.
Some of these heavy metals such as copper and bismuth are not produced in the NL. Other heavy metals such as zinc, iron and steel are produced in the NL and will be modelled on the basis of the socio-economic variables. The lead content can be estimated on the basis of the amount of lead that remains as a contaminant in these heavy metals. The outflow will be determined on the basis of a distribution between different destinations (air, water, landfills, road materials, waste water purification system) as shown in figure 20.

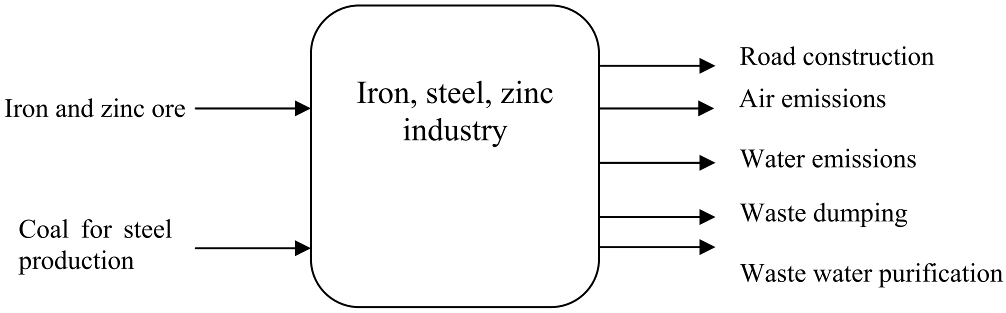

Figure 20: Lead inflow into the Dutch economy through other heavy metals and its outflow

Deriving model equations of other heavy metals

<u>Deriving a model equation of the inflow of zinc into the Dutch economy (1980-2000)</u>

The inflow of zinc into the Dutch economy in the past (figure 21) (British Geological Survey (1988-2000) & Metallgesellschaft, 1990) has been tested for correlation with different factors such as the population size, GDP, per capita GDP, and zinc price.

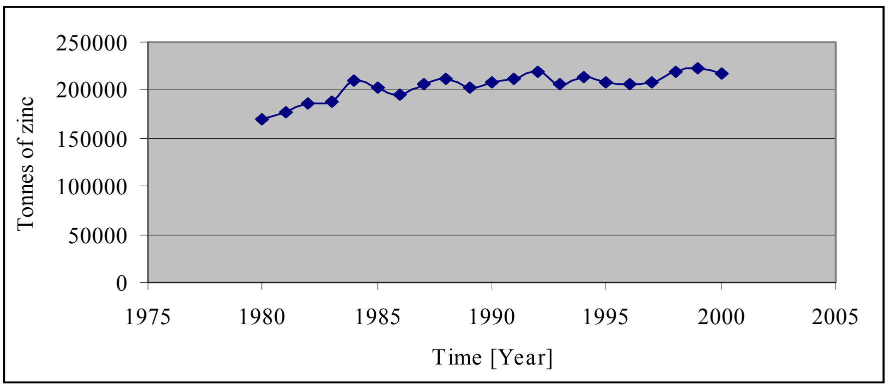

Figure 21: The inflow of zinc into the Dutch economy from 1980 through 2000

The results indicate a positive correlation between the inflow of zinc and all tested variables. The correlation between the inflow of zinc and population, GDP, per capita GDP and the price is significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high with the exception of the price. When variables such as GDP and population or GDP and price were combined, the GDP and price variables lose their significance and the coefficient of determination does not change significantly from the one associated with the population. Therefore, the following model will be used to calculate the inflow of zinc:

$$Inflow\ (t) = -87610 + 0.01947 * Population(t) \qquad (70)$$

The past and future inflow of zinc based on Equation 70 is shown in figure 22.

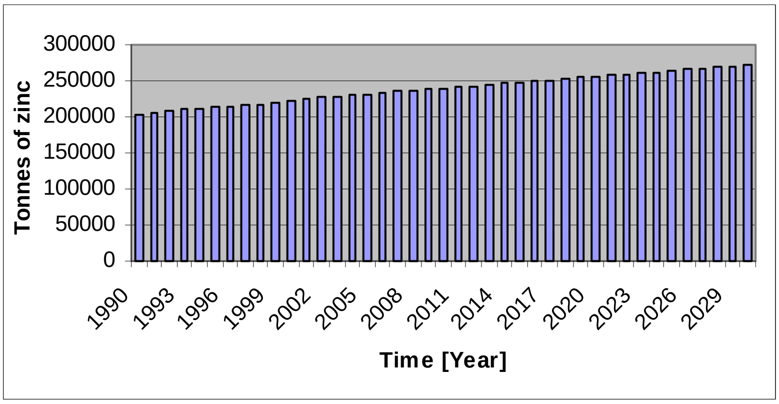

Figure 22: Past and future inflow of zinc into the Dutch economy

<u>Deriving a model equation of the inflow of iron into the Dutch economy (1990-2000)</u>

The inflow of iron into the Dutch economy in the past (figure 23) (British Geological Survey (1988-2000)) has been tested for correlation with different factors such as the population size, GDP, and per capita GDP.

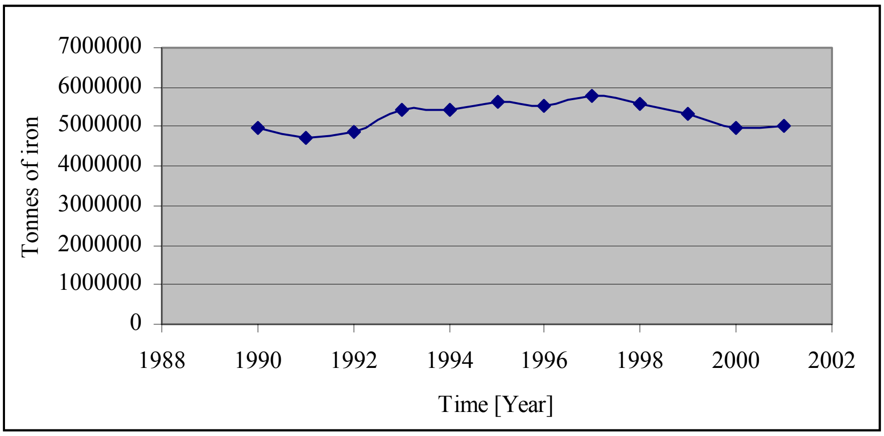

Figure 23: The inflow of iron into the Dutch economy from 1990 through 2001

The results indicate a positive correlation between the inflow of iron and all tested variables. The correlation between the inflow of iron and GDP, and per capita GDP is significant at the 99% probability level. The correlation between the inflow of iron and the population is not significant. The coefficient of determination (R^2) associated with the correlation is fairly high except for the variable population. When variables such as GDP and population were combined, the coefficient of determination does not change significantly from the one associated with the per capita GDP. Therefore, the following model will be used to calculate the inflow of iron:

$$Inflow\ (t) = 2.94E6 + 10.4078 * GDP/C(t) \qquad (71)$$

The past and future inflow of iron based on Equation 71 is shown in figure 24

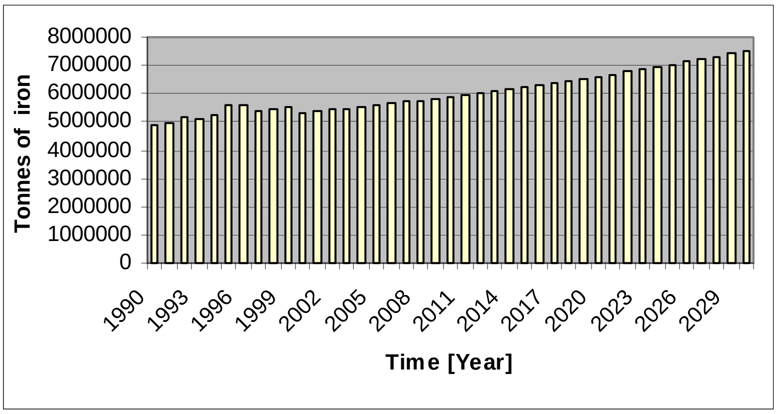

Figure 24: Past and future inflow of iron into the Dutch economy

<u>Deriving a model equation of the inflow of steel into the Dutch economy (1990-2000)</u>

The inflow of steel into the Dutch economy in the past (figure 25) (British Geological Survey (1988-2000)) has been tested for correlation with different factors such as the population size, GDP, and per capita GDP.

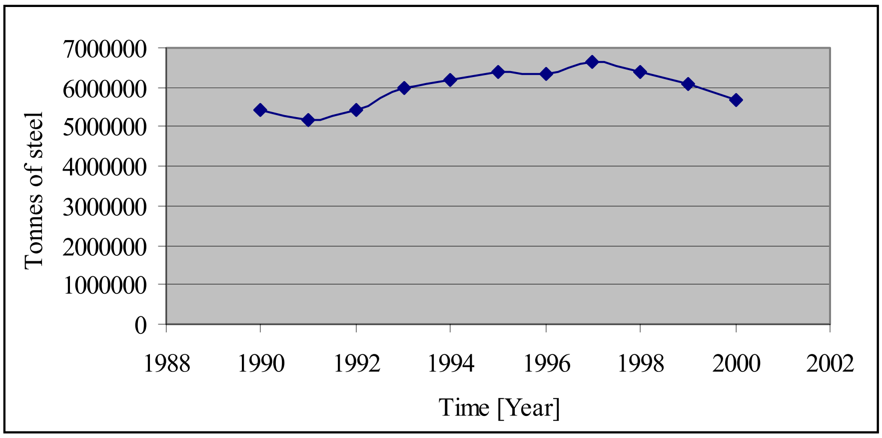

Figure 25: The inflow of steel into the Dutch economy from 1990 through 2001

The results indicate a positive correlation between the inflow of steel and all tested variables. The correlation between the inflow of steel and GDP, and per capita GDP is significant at the 99% probability level. The correlation between the inflow of steel and the population is significant at the 95% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high with the exception of the population. When variables such as GDP and population were combined, the coefficient of determination does not change significantly from the one associated with the per capita GDP. Therefore, the following model will be used to calculate the inflow of steel:

$$Inflow(t) = 2.5E6 + 15.3636 * GDP/C\ (t) \qquad (72)$$

The past and future inflow of steel based on Equation 72 is shown in figure 26

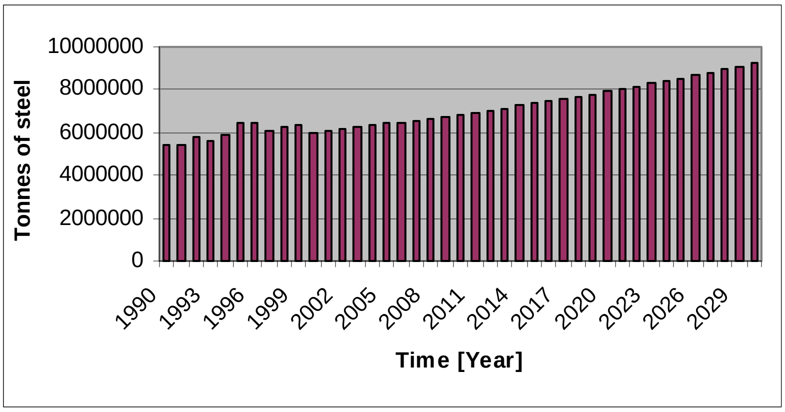

Figure 26: Past and future inflow of steel into the Dutch economy

Lead inflow into the Dutch economy through the inflow of iron and zinc

The inflow of lead into the Dutch economy through the inflow of zinc and iron in 1990 is estimated as 6506 ton of lead (Annema et. al., 1995). In order to separate the amount of lead related to zinc from the amount of lead related to iron, first the inflow of lead through zinc is estimated, and then the inflow of lead through the inflow of iron is estimated as the difference between the total inflow of lead through both iron and zinc and the inflow of lead through the inflow of zinc. The inflow of lead through zinc is estimated based on the amount of zinc produced in the NL in 1990 and the percentage of lead in crude zinc (1.85%) (Ally et. al., 2001).

The inflow of lead into the Dutch economy in the past and the future through the inflow of iron and zinc is estimated as 0.019 ton of lead per ton of produced zinc and 0.0005 ton of lead per ton of produced iron. The inflow of lead is shown in figure 27.

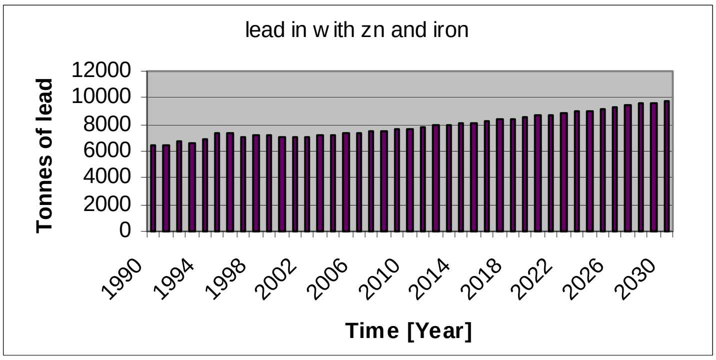

Figure 27: The inflow of lead into the Dutch economy through the inflow of zinc and iron

Lead inflow into the Dutch economy through the inflow of coal used for steel production

The inflow of lead into the Dutch economy through the use of coal in steel production is estimated based on the inflow of lead through the inflow of coal in 1990, which is estimated as 45 ton of lead (Annema et. al., 1995), divided by the produced steel in same year. The inflow of lead into the Dutch economy in the past and the future through the use of coal in steel production is estimated as 8.31793E-6 ton of lead per ton of produced steel. The inflow of lead is shown in figure 28.

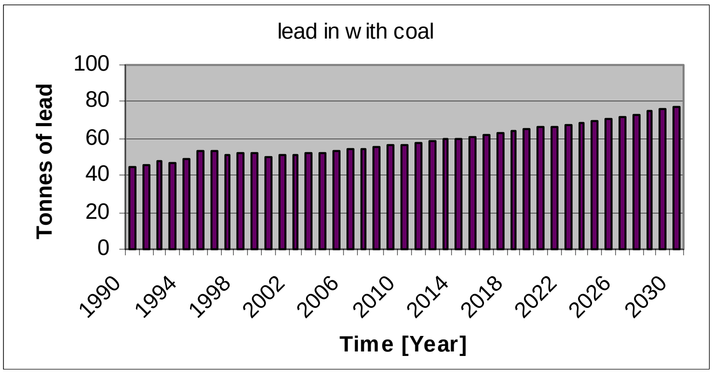

Figure 28: The inflow of lead into the Dutch economy through the inflow of coal used for steel production

Lead outflow from the production of zinc, iron and steel in the Dutch economy

Lead outflow from the production processes of zinc, iron and steel is equal to the inflow. Lead outflow is distributed between different destinations. 1.908% of the outflow ended up in materials used in road construction, 0.732% of the outflow is emitted to air, 0.0458% of the outflow is emitted to surface water, 0.106% of the outflow ended up in the waste water purification system, and 97.206% of the outflow ended up in landfills. This distribution is based on the amount of lead which ended up in the different destinations in 1990 (Annema et. al., 1995), divided by the total outflow in the same year. Lead outflow to the different destinations is shown in figures 29, 30, 31, 32 and 33.

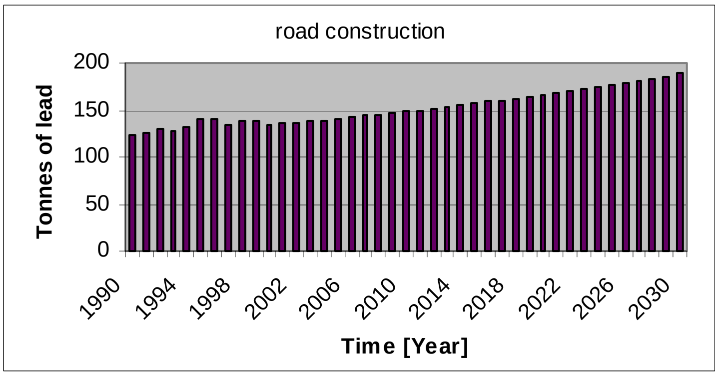

Figure 29: Lead outflow from the production of other heavy metals to road construction

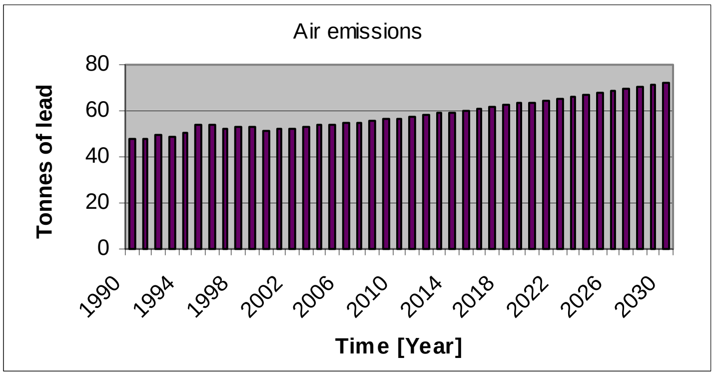

Figure 30: Lead emissions to air during the production of other heavy metals

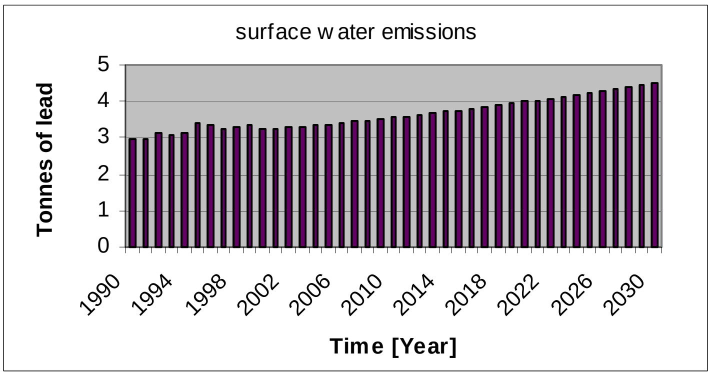

Figure 31: Lead emissions to surface water during the production of other heavy metals

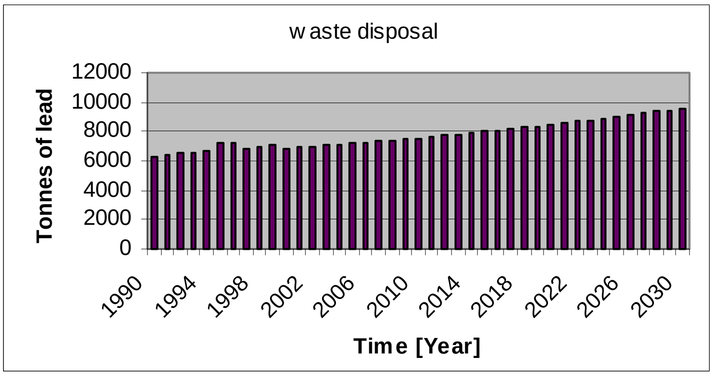

Figure 32: Lead outflow from the production of other heavy metals to landfill

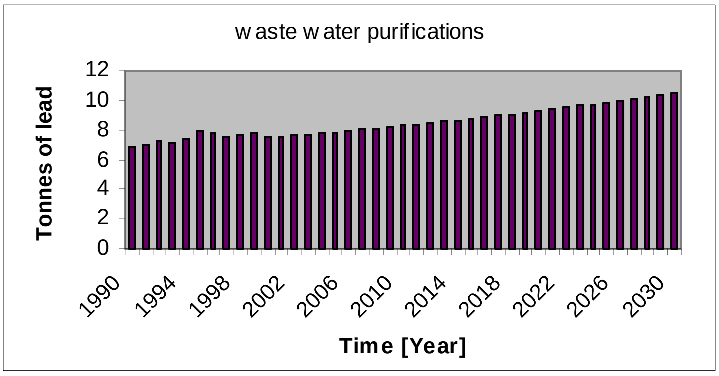

Figure 33: Lead outflow from the production of other heavy metals to the waste water purification system.

6.2.2.2.2 Lead in fossil fuels

Lead is present as a contaminant in fossil fuels (oil and coal). In this case, the emissions of lead as a result of the consumption of fossil fuels should be estimated on the basis of the current use and future demand of fossil fuels which in turn either can be estimated as a function of the socio-economic factors or from external forecasting models of energy.

Lead inflow and outflow due to the electricity production from coal and oil

The total electricity produced in the NL and the main sources used in the electricity production are shown in figure 34 (CBS, 2003).

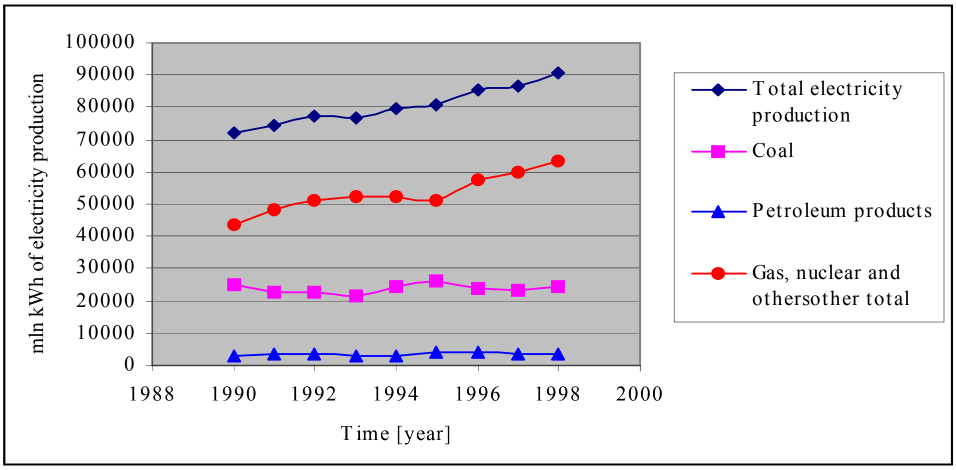

Figure 34: Total electricity production and its main sources in the NL

<u>Deriving a model equation of the total electricity production and the main sources used in the production (1990-1998)</u>

a. Total electricity production

The production of electricity in the NL in the past (figure 28) has been tested for correlation with different factors such as the population size, GDP, and per capita GDP. The results indicate a positive correlation between all tested variables and the production of electricity, significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high. The best correlation is the one with the population. When variables such as GDP and population were combined, the coefficient of determination does not changed significantly from the one associated with the population. Therefore, the following model will be used to calculate the total electricity production in the NL:

*Total electricity production (t) =-3.11E5+2.55E-2*Pop(t)* (73)

The future electricity production based on Equation 73 is shown in figure 35.

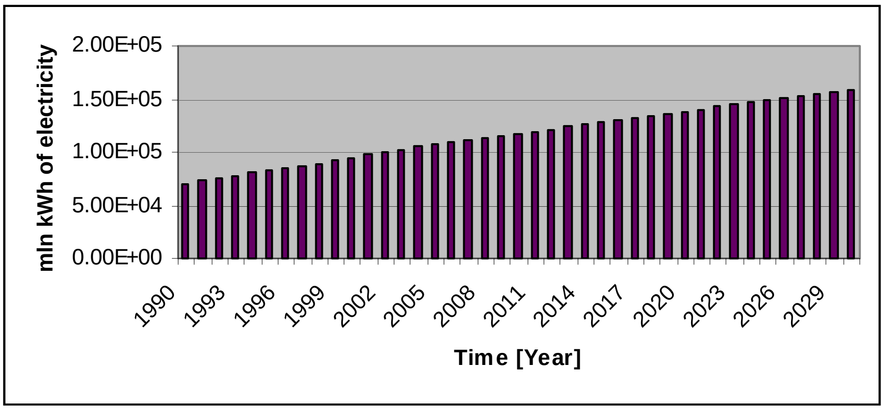

Figure 35: Past and future demand for electricity in the NL

b. Electricity produced from gas, nuclear and other sources

The production of electricity in the NL from gas, nuclear and other sources than oil and coal in the past (figure 34) has been tested with different factors such as the population size, GDP, and per capita GDP. The results indicate a positive correlation between all tested variables and the production of electricity from these sources, significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high. The best correlation is the one with the population. When variables such as GDP and population were combined, the coefficient of determination does not change significantly from the one associated with the population. Therefore, the following model will be used to calculate the electricity production from gas, nuclear and other sources in the NL:

*Electricity produced from gas and other sources(t) =-308054+0.02351*Pop(t)* (74)

The future electricity production from gas, nuclear and other sources based on Equation 74 is shown in figure 36.

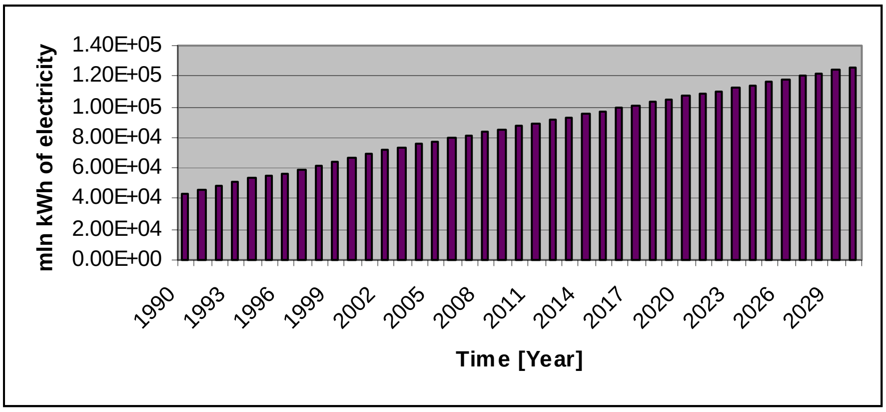

Figure 36: Past and future electricity production from gas, nuclear and other sources in the NL

c. Electricity produced from oil

The production of electricity in the NL from oil in the past (figure 34) has been tested with different factors such as the population size, GDP, and per capita GDP. The results indicate a positive correlation between all tested variables and the production of electricity from oil. The correlation between the electricity production from oil and GDP, per capita GDP is significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high. The best correlation is the one with the per capita GDP. When variables such as GDP and population were combined, the coefficient of determination does not change significantly from the one associated with the per capita GDP and the population is not significant and has unexpected negative sign. Therefore, the following model will be used to calculate the electricity production from oil in the NL:

*Electricity produced from oil (t) = 986.53+0.01092 *GDP/C(t)* *(75)*

The future electricity production from oil based on Equation 75 is shown in figure 37.

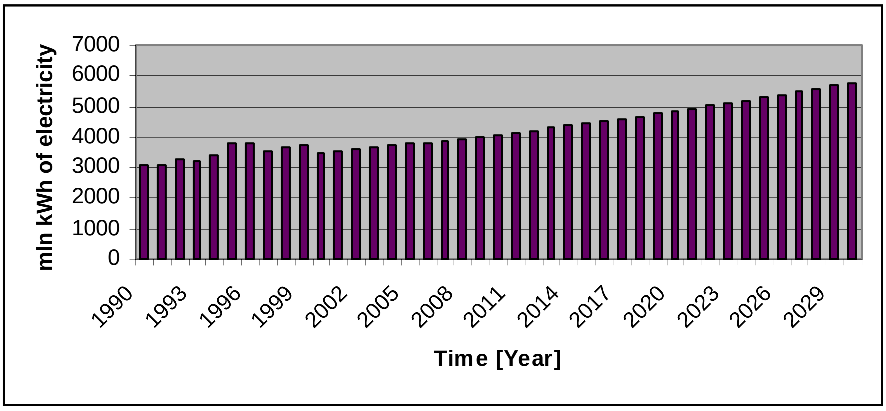

Figure 37: Past and future electricity production from oil in the NL

d. Electricity produced from coal

The production of electricity in the NL from coal is estimated as the total electricity production in the NL minus the produced electricity from other sources as given by:

Electricity produced from coal = total electricity -Σ electricity produced from other sources *(76)*

The future electricity production from coal based on Equation 76 is shown in figure 38.

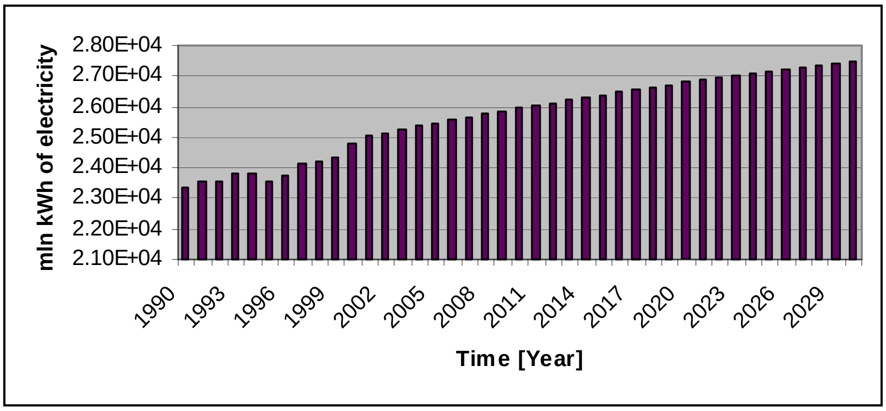

Figure 38: Past and future electricity production from coal in the NL

Lead emissions to air during the production of electricity from oil

The emissions of lead due to the use of oil in electricity production are estimated on the basis of 0.128 kg lead per 1TJ electricity production (ETH database). Figure 39 shows the emissions of lead during the electricity production from oil.

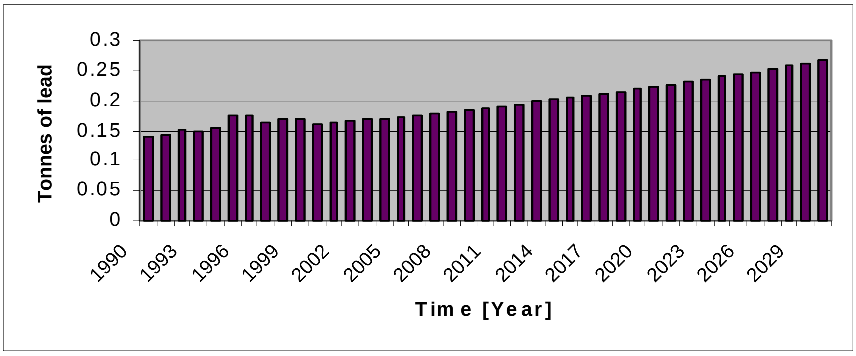

Figure 39: Lead emissions to air due to the use of oil in electricity production

Inflow of lead through coal used in electricity production

The inflow of lead through coal used in the production of electricity is estimated based on the inflow of lead through coal in 1990 (Annema et. al., 1995), and the electricity produced from coal in the same year. The inflow of lead through coal used in the production of electricity is estimated as 0.00913 ton of lead per mln kWh of electricity produced. Figure 40 shows the inflow of lead through coal used in electricity production.

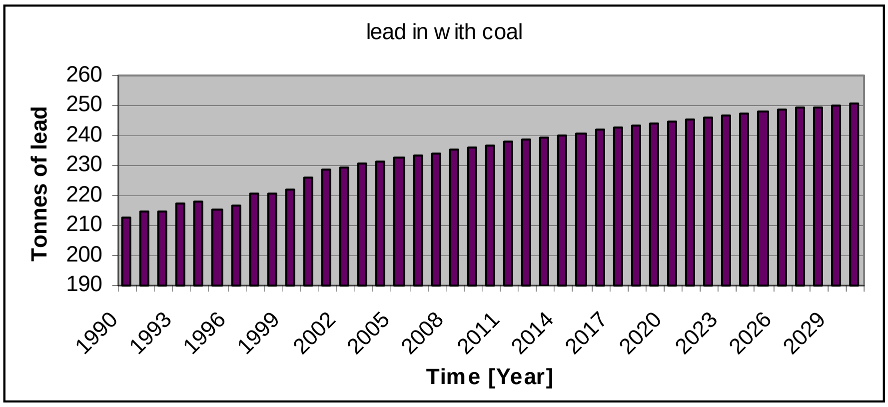

Figure 40: The inflow of lead into the Dutch economy through the coal used in electricity production

Outflow of lead from coal power plants

Lead outflow from the production of electricity from coal is equal to the inflow of lead through coal used in electricity production. Lead outflow is distributed between different destinations. 40.18% of the outflow ended up in materials used in road construction, 0.46% of the outflow is emitted to air, and 59.34% of the outflow ended up in materials used in buildings. This distribution is based on the amount of lead ended up in the different destinations in 1990 (Annema et. al., 1995), divided by the total outflow in the same year. Lead outflow to the different destinations is shown in figures 41, 42 and 43.

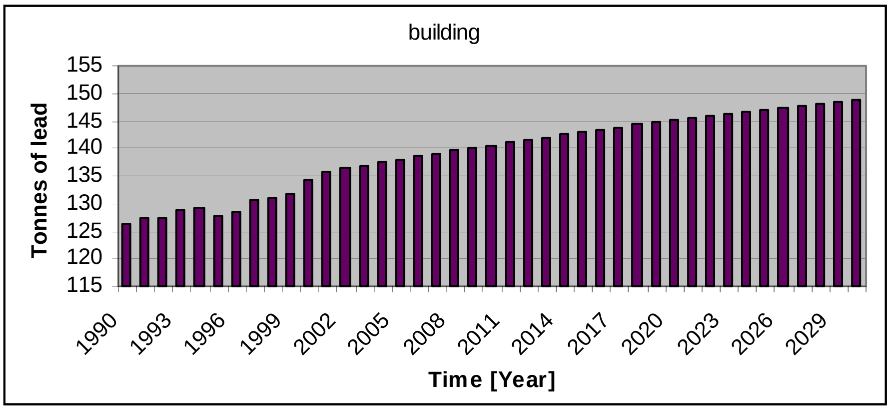

Figure 41: Lead outflow from coal power plants to buildings

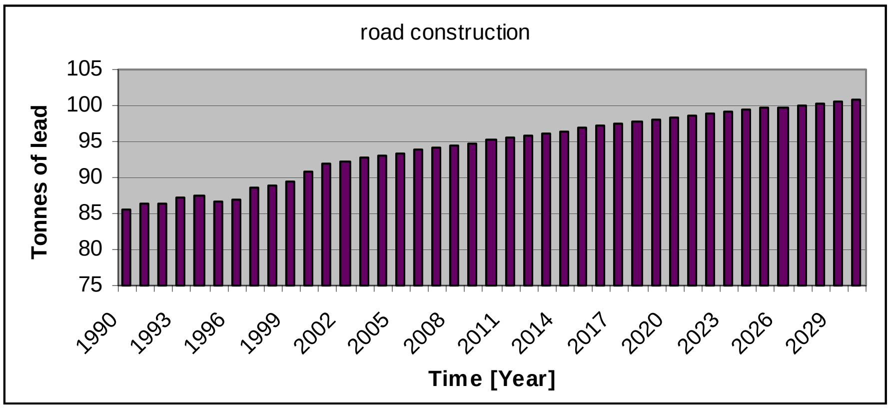

Figure 42: Lead outflow from coal power plant to road construction

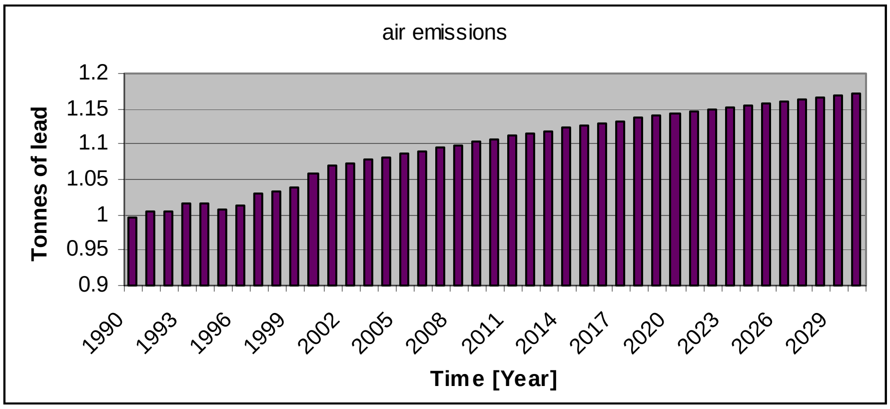

Figure 43: Lead emissions to air during the production of electricity from coal

6.2.2.2.3 *Lead in refined oil*

The production of refined oil in the NL in the past (figure 44) (CBS, 2003) has been tested with different factors such as the population size, GDP, and per capita GDP. The results indicate a positive correlation between all tested variables and the production of oil, significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is high. When variables such as GDP and population were combined, the coefficient of determination does not change significantly from the one associated with the GDP or per capita GDP and both variables turn out to be insignificant. Therefore, the following model will be used to calculate oil production in the NL:

$$\textit{Oil production}(t) = 35547 + 5.63E\text{-}9 * GDP(t) \qquad (77)$$

The future oil production based on Equation 77 is shown in figure 45.

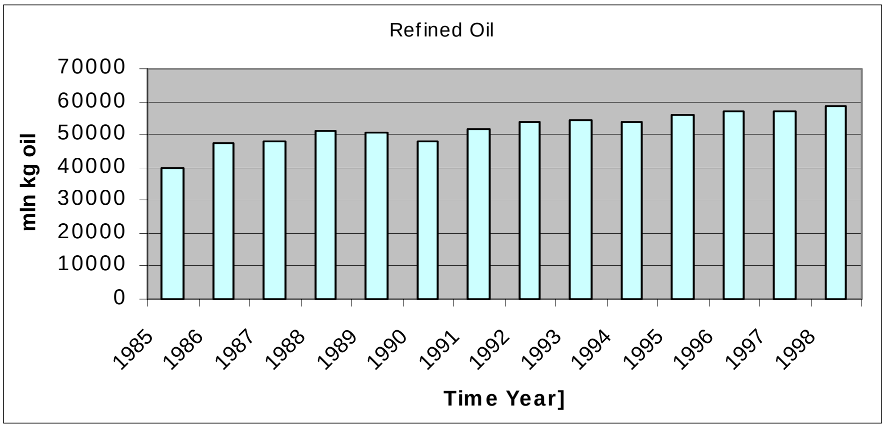

Figure 44: Production of refined oil in the NL in the past

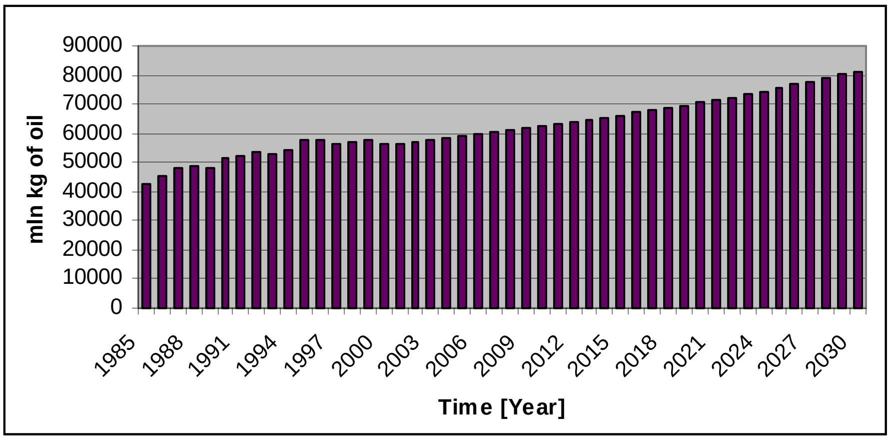

Figure 45: Past and future oil production in the NL

<u>Outflow of lead from the oil production processes</u>

Lead outflow from refined oil production to the environment is estimated directly from the produced amount of oil. The emitted outflow to air is estimated as 0.0001646 kg of lead per ton of produced oil, the emitted outflow to water is estimated as 0.0003376 kg of lead per ton of produced oil, and the emitted outflow to soil is estimated as 0.0000345 kg of lead per ton of produced oil (ETH database). Lead outflow to the different destinations is shown in figure 46.
Lead might exist in refined oil and consequently in the products that oil is used in their production. These products are not included in the model.

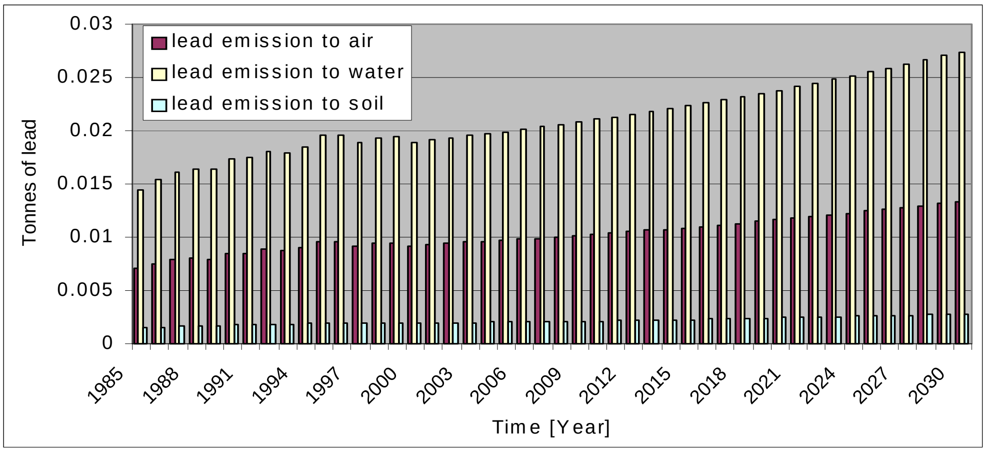

Figure 46: Lead emissions to air, water and soil during the production processes of oil

6.2.2.2.4 Lead in fertilizers

Lead occurs as a contaminant in chemical fertilizers due to the natural existence of lead in the ores from which these fertilizers are made, especially the phosphate ores. To estimate the amount of lead in fertilizers, a model for the use of fertilizer has to be made. Alternatively, a developed scenario by the RIVM can be used.

Nutrients (nitrogen, phosphorous and potassium) are essential elements for plant growth and crop production. Their requirements can be fixed either naturally or artificially. In the past, farmers tended to intensify the agricultural production, as a consequence of the higher prices of the agricultural output and increased demand, but especially as a consequence of EU agricultural policy, by implementing more fertilizers to maximize the yield. The increased use of fertilizers and manure has resulted in an excess of the nutrients in the environment and consequently several environmental problems.
Some of these environmental problems are related to the application of fertilizers and manure in the agricultural soil, such as eutrophication of surface waters, decreasing quality of ground water, decreasing biodiversity and quality of natural ecosystem and soil acidification (Wolf et al. 2003). Others are related to the production of fertilizers, which is known as an energy intensive industry (Worrell et al. 1995) and the refining of phosphate rock, which leads to enormous amounts of contaminated (and therefore hardly usable) gypsum.
Due to these environmental problems, several international environmental agreements have been made such as the 1985 North Sea Treaty, which lays down a 50% reduction

in nitrogen and phosphate leaching to the North Sea. In the EU, different environmental policy measures have been taken such as applying fertilizers tax, reducing agricultural price support (Mergos & Stoforos, 1997), levies and tradable quotas (Hasler, 1998). There are also policies aimed at putting limits to the concentration of heavy metals in fertilizers (especially cadmium). This means either a shift to cleaner ores, or taking out the metals in the refining process.
These policy measures aim at reducing the use of manure and chemical fertilizers as a way to reduce leaching of phosphate and nitrate to ground and surface water and to reduce the use of energy in the production processes and consequently a reduction in the CO_2 and N_2O emissions.

The main influential factors affecting the use of fertilizers

The use of fertilizers is affected by different factors. In the past, the increase in the use of fertilizers has been connected to the demand for agricultural products which is increasing along with the economic developments in a country or a region (Bouwman & Hoek) and population growth. Moreover, the price of fertilizers is an important factor in determining its use. The price of fertilizers is part of the total cost of farming (10-20% of the total cost (Bockman et al. 1990)). When the price of fertilizers goes up, farmers tend to use less fertilizer, however, this is not always a straightforward relation. Sometimes the agriculture output price increases faster than the price of fertilizers, thus farmers could increase their fertilizer use economically.
Moreover, the agriculture output price is affecting the producer's decision in increasing the production and thus using more fertilizers. The effect of the output price, however, is not related to the demand in the same year but is a lagged effect.
Also the EU agricultural policy has had a large influence. For a long time their goals of self-sufficiency and good farmers income has been reached by protecting the European market, so prices would stay high even if world market prices would drop. Presently the EU policy is somewhat modified, under the pressure of surplus production but also because of the increasing environmental problems caused by the agricultural sector.

The Dutch fertilizers policy

The minerals policy in the Netherlands is introduced in the 1980s and has been implemented in phases. From 1987 through 1990, the government focused on stopping the manure surplus from growing. From 1990 through 1998, the government aimed to reduce the environmental burden of the manure surplus. The goal of the current phase is to achieve a balance in the supply and demand of nitrogen and phosphate.
The reduction in chemical fertilizer use between 1986 and 1998 was mainly due to intensive campaigns and farm consultancy, which also lead to a considerable improvement of farmer's utilization of animal manure. In 1998, the mineral accounting system was introduced and has led to a further reduction. In 2002, the system of manure transfer through domestic contracts or export came into force, which may lead to a further reduction.
Introducing Minas in 1998, policy aimed at lowering the N and P emissions from agriculture by 50% compared to 1985 (Wolf et al 2003). Minas has several advantages compared to the old policy: policy no longer focuses on phosphate alone but explicitly includes nitrogen (in the past nitrogen reduction was only indirect effect of policy), policy addresses mineral surplus as a true problem and measures therefore apply to

animal manure, chemical fertilizers and other organic fertilizers (in the past chemical fertilizers were ignored), and shifting policy from specifying measures to setting targets.

Past inflow of phosphate fertilizers (1961-2000)

The past inflow of fertilizers into the Dutch agriculture system is the amount of nitrogen, phosphorous and potassium fertilizers used in the plant and crop production. Figure 47 shows the inflow of phosphate fertilizers into the Dutch economy from 1961 through 1995 (FAO). The past inflow is determined by several factors such as the economic growth, population growth, fertilizers price, the producer price of agricultural products, the relative price of fertilizers with respect to the price of agricultural output, lagged agricultural output price and policy measures.

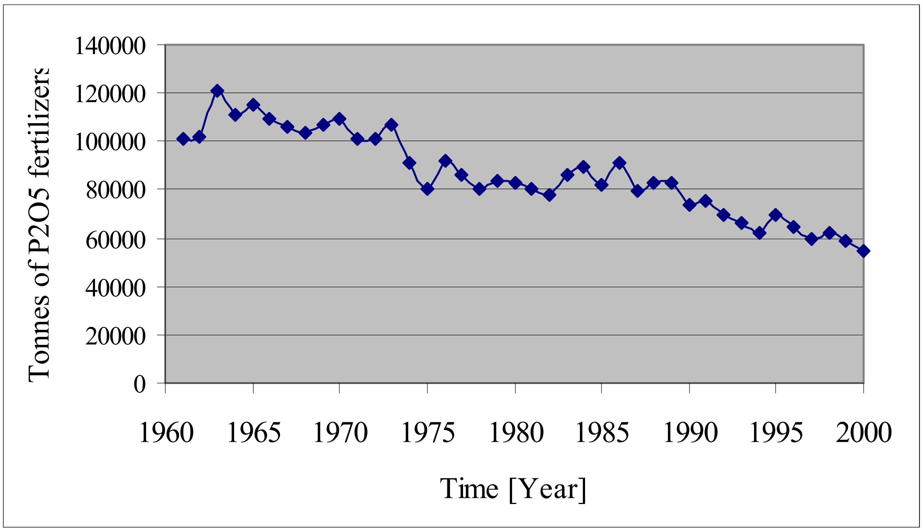

Figure 47: The inflow of phosphate fertilizers to the Dutch agriculture soil from 1961 through 2000

Deriving a model equation of the inflow of phosphate fertilizers

To evaluate the effect of the different factors on the inflow, regression analysis is used. In the model, a general function (Eq.11) is used to describe the inflow based on past trend data:
The explanatory variables that are used in the analysis are population size, GDP, per capita GDP, agricultural output price, population growth and the time as a proxy of the effect of other influential variables on the inflow of phosphate fertilizers. The analysis is made from 1961 through 2000, except for the price for which the analysis is made from 1966 through 1995.
The coefficient of determination (R^2) associated with all correlations is fairly high. It is clear from the analysis of the inflow that all the independent variables correlate negatively with the inflow, except the population growth. This is according to the initial expectations because the fertilizer use is declining and the variables (except population growth) are increasing. This means the development in fertilizer use is difficult to explain from variables such as GDP, population, per capita GDP or the price. It is clear that policy has a large influence on the decline in fertilizer use. However, the future use of fertilizer can be estimated using the time as explanatory variable since it could

capture the influence of the policy on fertilizer use. Therefore, the following model will be used to calculate the future demand for phosphate fertilizers in the NL:

$$\text{Inflow of fertilizers } (t) = 114932 - 1386 * \text{time} \qquad (78)$$

The past measured inflow of fertilizers and the future inflow based on Equation 78 is shown in figure 48.

Using equation 78 lead to a continuous decrease of the inflow, which is on the long term might not be the case. At some point the inflow might level of. This development can be included using a certain scenario.

Scenario for the future use of fertilizers

Two scenarios have been developed by RIVM (Egmond et al. 2001) to estimate the future use of manure and artificial fertilizers in the Dutch agricultural system. These scenarios are based on the current policy of the Dutch government. The impact of the policy is determined by the willingness of the farmers to sign disposal contracts. The first scenario (VAC) is based on the assumption that many contracts will be made and thus the distribution of manure will be efficient. The second scenario (WAC) is based on the assumption that only a few contracts will be made. The use of artificial fertilizers in the future (from 2003 through 2030) on the basis of the two scenarios is shown in table 1 and 2.

Table 1: The past, present and future use of N- fertilizers (mln kg)

	1990	1995	1997	2003	2010	2020	2030
VAC Scenario	**404**	**398**	**390**	**242**	**242**	**232**	**228**
WAC Scenario	**404**	**398**	**390**	**283**	**270**	**260**	**259**

Table 2: The past, present and future use of P2O5- fertilizers (mln kg)

	1990	1995	1997	2003	2010	2020	2030
VAC Scenario	**76**	**62**	**64**	**63**	**40**	**38**	**38**
WAC Scenario	**76**	**62**	**64**	**63**	**40**	**38**	**38**

The values of past and future use of P_2O_5 in the two scenarios are depicted in figure 48

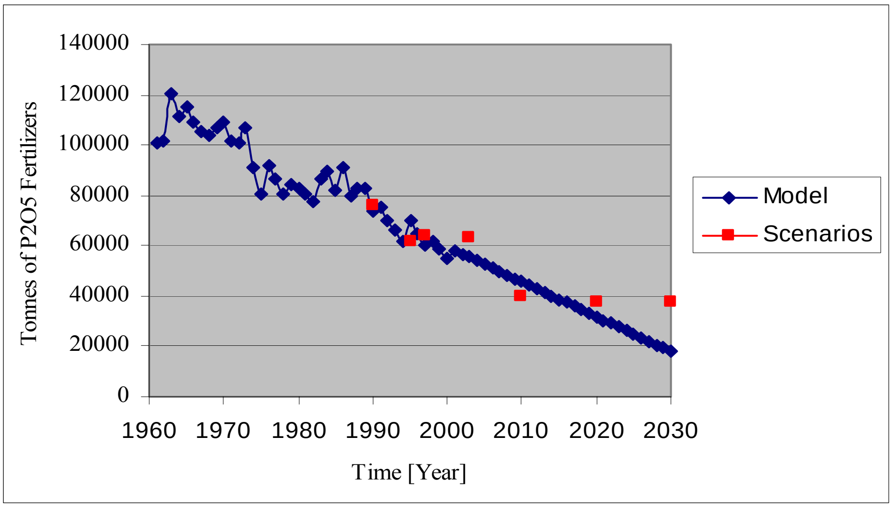

Figure 48: The past and future inflow of phosphate fertilizers into the Dutch agricultural soil based on the model and the RIVM scenarios

<u>The inflow of lead through the inflow of phosphate fertilizers</u>

The inflow of lead into the agricultural soil through phosphate fertilizers is estimated based on the inflow of lead through fertilizers in 1990 (CBS, 1993), and the total phosphate fertilizers used in the Dutch agricultural soil in the same year (FAO).
The inflow of lead into the agricultural soil through the inflow of phosphate fertilizers is estimated as 0.000135 ton of lead per ton of phosphate fertilizers. Figure 49 shows the inflow of lead through the inflow of phosphate fertilizers. The future inflow of fertilizers is estimated as given by Eq. 78.

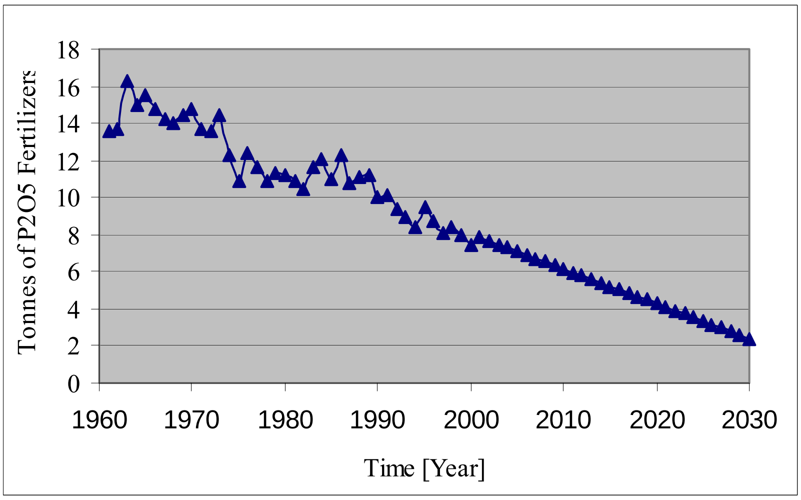

Figure 49: The inflow of lead in the past and the future into the Dutch agricultural soil

6.3. Waste management of different lead applications

The discarded outflow of some lead applications such as batteries, lead sheet, CRTs and small vehicle applications is either collected for recycling or ended up in the incineration plants and landfill sites. For other applications such as ammunition and cable sheathing, the discarded outflow is either collected for recycling or remained in soil. For these two applications, the total collected, incinerated and landfilled fractions are not equal to 1.

6.3.1. Collection of waste stream of lead containing products

The past and future collected waste stream from the discarded products is estimated as a fraction of the total past and future discarded waste stream from the use phase. The collection rate is changing over time. Therefore, it can be estimated either by regression analysis or it can be left as a parameter to be adjusted in a scenario. For lead sheet in buildings, the collection rate is analyzed using regression analysis. For other applications, due to the lack of time series, the collection rate will be left as a parameter to be adjusted.

Deriving a model equation of the collection rate of lead sheet in buildings (1993-2000)

The collection rate of lead sheet in the NL in the past has been tested with different factors such as the population density, and per capita GDP. The results indicate a positive correlation between all tested variables and the collection rate, significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high. When the two variables were combined, the coefficient of determination has changed significantly from the one associated with each of them separately and both are still significant. Therefore, the following model will be used to calculate the collection rate of lead sheet in the NL:

$$\text{Collection rate }(t) = -234.16+(0.612*PopD(t))+(0.000179*GDP/C(t)) \quad (79)$$

The past and future collection rate based on Equation 79 is shown in figure 50.

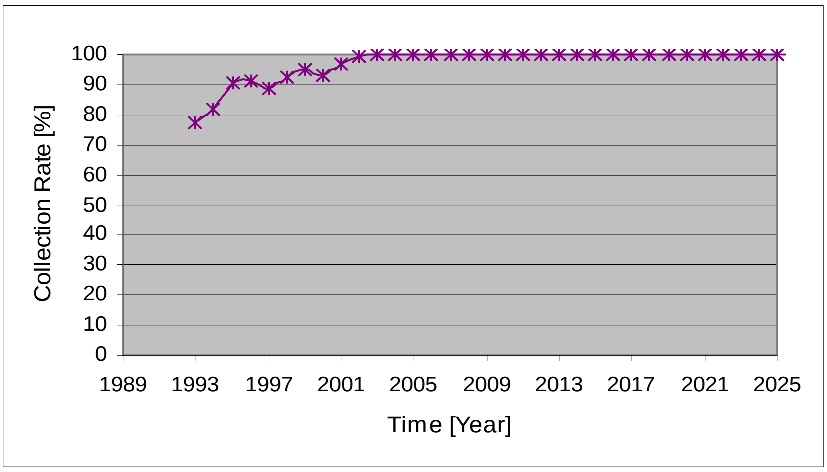

Figure 50: past and future collection rate of lead sheet in buildings

6.3.2. Collection rate of other lead containing applications

The collection rate (CR) of other lead containing applications is assumed to be either increasing over time or constant. The following equations for the collection rate of other lead containing applications are used in the model.

Collection rate of SLI batteries

$$CR_{SLI} = 0.945 + (0.005*time) \tag{80}$$

Collection rate of traction batteries

$$CR_{Traction} = 0.945 + (0.005*time) \tag{81}$$

Collection rate of industrial batteries

$$CR_{Industrial} = 1.0 \tag{82}$$

Collection rate of cable sheathings

$$CR_{cables} = 0.75 \tag{83}$$

Collection rate of CRTs

$$CR_{CRTs} = 0.49 +(0.01*time) \tag{84}$$

Collection rate of small vehicle applications

$$CR_{SVA} = 0.0 \tag{85}$$

Collection rate of ammunition

$$CR_{Ammunition}= 0.5 \tag{86}$$

Using these equations, the collection of lead in different applications in the future is shown in figure 51 and 52.

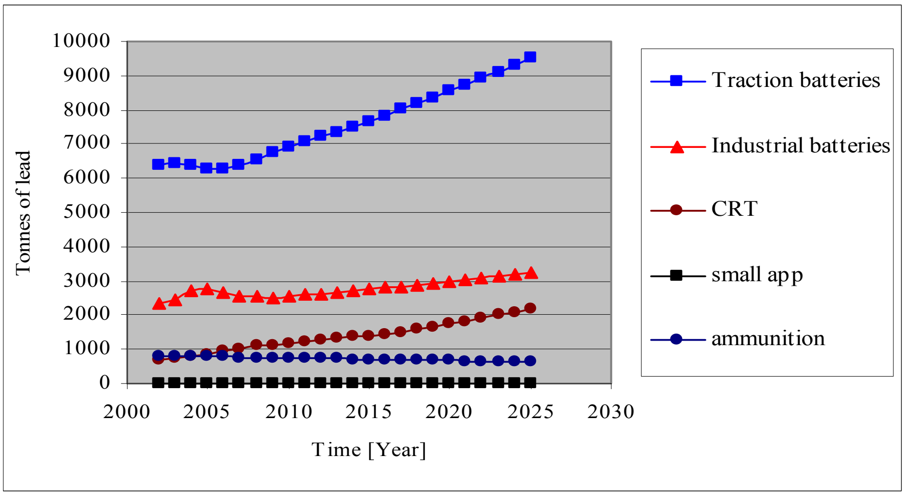

Figure 51: The collection of traction batteries, industrial batteries, CRTs, small vehicle applications and ammunition in the NL in the future

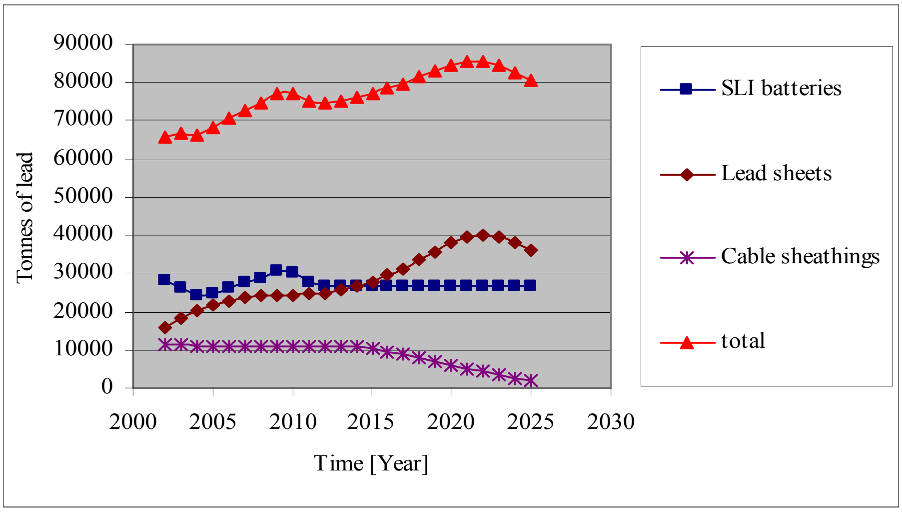

Figure 52: The collection of SLI batteries, lead sheet and cable sheathing and the total collected lead from all applications in the NL in the future

6.3.3. Incineration processes

6.3.3.1. Inflow of lead into the incineration

The inflow of lead into the incineration plants originates from two sources: the waste stream of lead containing products discarded from the use phase, and sewage sludge.

Waste stream of lead containing products discarded from the use phase

The inflow of lead into the incineration plants from the waste stream of lead containing products discarded from the consumption phase is estimated together with the waste flow to-be-landfilled. Both are estimated as the difference between the total discarded waste stream and the collected waste stream. The incinerated flow thus is estimated as a fraction of the total not-collected flow (Tukker et. al.).
The following equations are used to calculate the incineration rate (IR) of lead containing applications:

$$IR_{LS} = 0.2 * (1- CR_{LS}) \quad (87)$$

$$IR_{SLI} = 0.3 * (1- CR_{SLI}) \quad (88)$$

$$IR_{Traction} = 0.3 * (1- CR_{Traction}) \quad (89)$$

$$IR_{Industrial} = 0.0 \quad (90)$$

$$IR_{cables} = 0.0 \quad (91)$$

$$IR_{CRTs} = 0.2 * (1- CR_{CRTs}) \quad (92)$$

$$IR_{SVA} = 0.25 * (1- CR_{SVA}) \quad (93)$$

$$IR_{Ammunition} = 0.0 \quad (94)$$

Using these equations, the incineration of lead in different applications in the future is shown in figure 53.

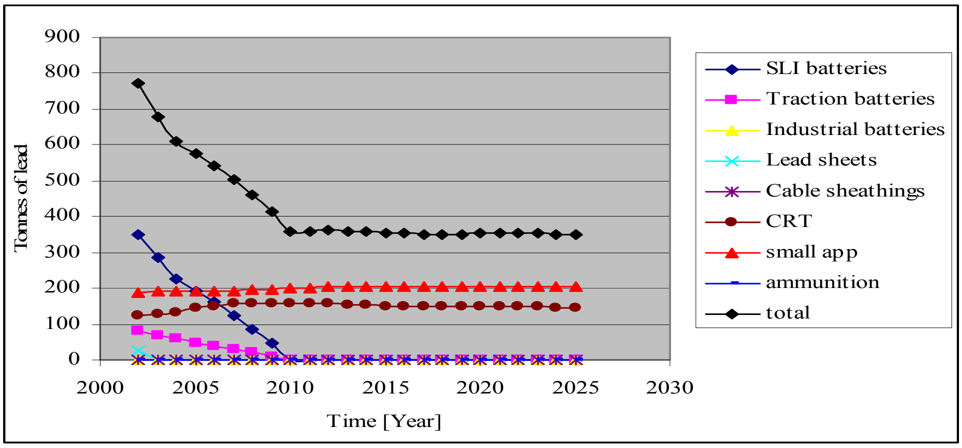

Figure 53: The incineration of different lead containing applications in the NL in the future

Lead in Sewage sludge

The inflow of lead into the incineration plants from sewage treatment is estimated as 62% of the total amount of lead in the sewage sludge (CBS, 2003). The remaining lead in sewage sludge has different destinations (landfill sites, agricultural soil and others) (see 6.6.2).

The inflow of lead to the incineration plants from the discarded waste stream is shown in figure 53 and the inflow from sewage sludge is shown in figure 54.

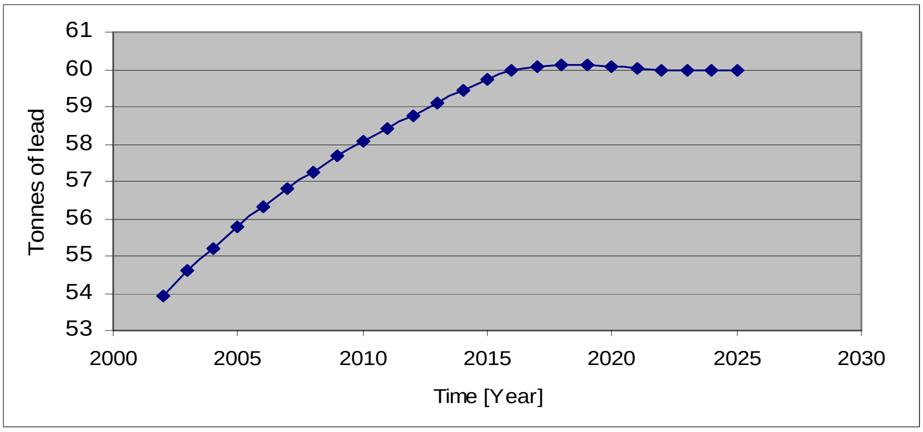

Figure 54: The inflow of lead from sewage sludge to the incineration plants in the NL in the future

6.3.3.2. Outflow of lead from the incineration

The incineration process has three outflows: fly ash, bottom ash and emissions to air. All of those outflows contain lead. The outflows of lead from the incineration plants in bottom ash, fly ash and air emissions are estimated as 68%, 32% and 0.07% respectively of the total inflow of lead to the incineration plants (Sloot, 1996 &Tukker et al. 2001). Figure 55 shows the outflow of lead from the incineration plants to the different destinations.

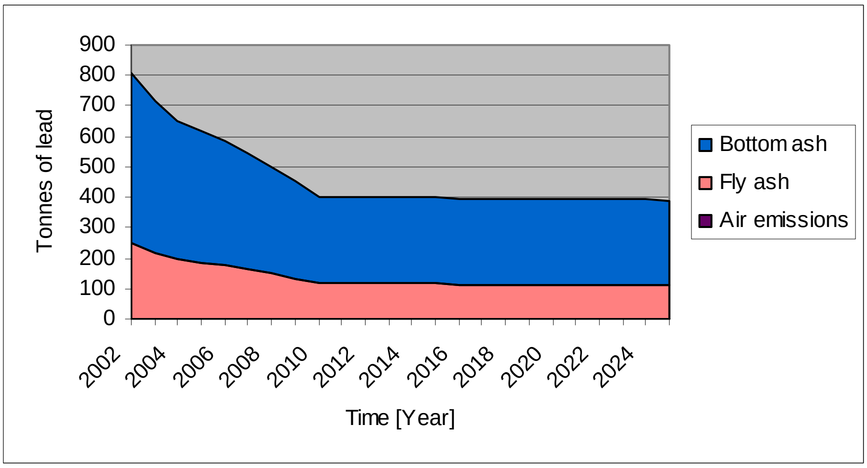

Figure 55: The outflow of lead from the incineration plants

6.3.4. Landfilling

6.3.4.1. Inflow of lead into landfill sites.

The inflow of lead to the landfill sites originates from different sources of waste streams: from production processes, from lead containing products discarded from the use phase, from the recycling processes, from bottom ash and fly ash, from sewage sludge, from construction materials, and from the production of other heavy metals

Waste stream of lead containing products discarded from the use phase

The inflow of lead into the landfill sites from the waste stream of lead containing products discarded from the consumption phase is estimated together with the waste flow to-be-incinerated. Both are estimated as the difference between the total discarded waste stream and the collected waste stream. The landfilled flow thus is estimated as a fraction of the total not-collected flow (Tukker et. al.). The following equations are used to calculate the landfill rate (LR):

$$LR_{LS} = 0.8 * (1- CR_{LS}) \quad (95)$$

$$LR_{SLI} = 0.7 * (1- CR_{SLI}) \quad (96)$$

$$LR_{Traction} = 0.7 * (1- CR_{Traction}) \quad (97)$$

$$LR_{Industrial} = 0.0 \quad (98)$$

$$LR_{cables} = 0.0 \quad (99)$$

$$LR_{CRTs} = 0.8 * (1- CR_{CRTs}) \quad (100)$$

$$LR_{SVA} = 0.75 * (1- CR_{SVA}) \quad (101)$$

$$LR_{Ammunition} = 0.0 \quad (102)$$

Using these equations, the landfilling of lead in different applications in the future is shown in figure 56.

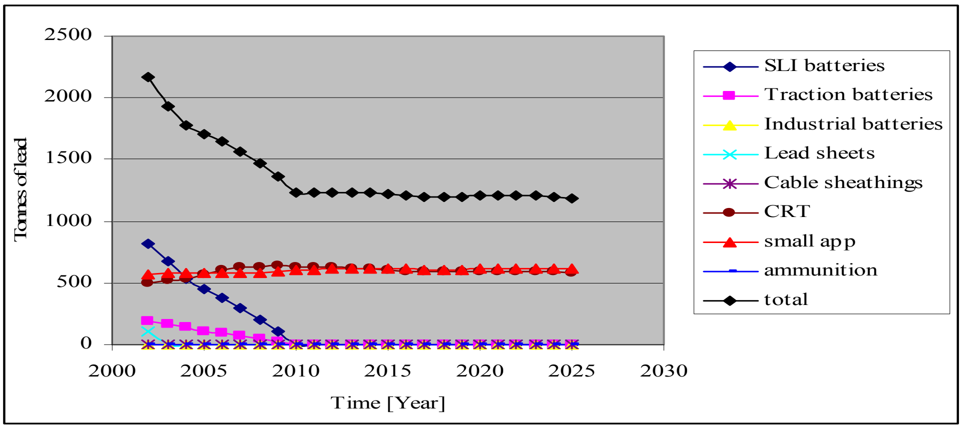

Figure 56: The landfilling of different lead containing applications in the NL in the future

Inflow of lead to the landfill sites from other sources

The inflow of lead into the landfill sites from the recycling processes is estimated as 0.445% of the produced refined lead (see 6.3.4.1). The inflows of lead from bottom ash and fly ash are estimated as balancing items of the use of aggregate and asphalt. The inflow of lead from sewage treatment is estimated as balancing item of the sewage treatment process. The inflow of lead from construction materials is estimated as a fraction of the construction materials discarded waste stream. The inflow of lead from the production of other heavy metals is estimated as 0.972 of the total inflow of lead through zinc, iron and coal used for steel production (see 6.2.2.2.1).
The inflow of lead to landfill sites from different sources is shown in figure 57.

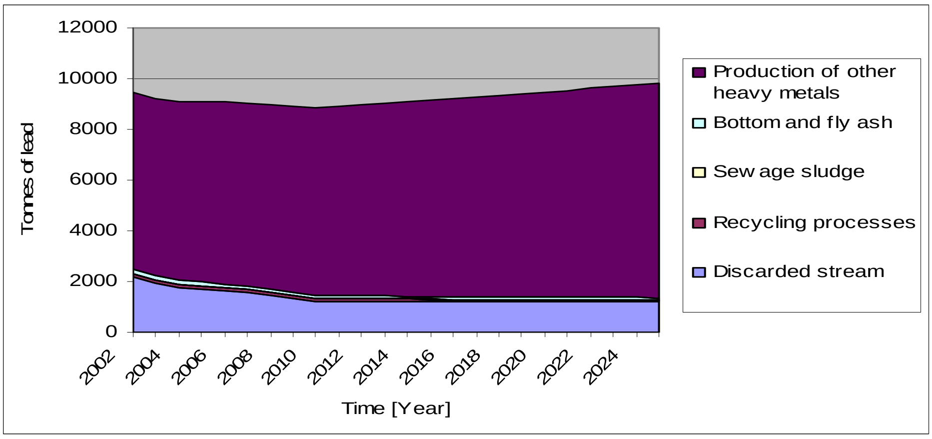

Figure 57: The inflow of lead from different sources to the landfill sites in the NL in the future

6.3.4.2. Outflow of lead from landfill sites

The outflow of lead from landfill sites takes place through the leakage of lead to water, which is estimated as 1.84E-5% of the stock (Tukker et al. 2001). The initial stock of lead in the landfill sites is unknown and difficult to estimate. Therefore, the stock and the outflow of lead from the stock-in-landfill sites are estimated from 2002 assuming the initial stock equal to zero. Consequently, the future estimates of the stock and the outflow of lead from landfill sites are underestimated. Figure 58 shows the stock in the landfill sites and figure 59 shows the outflow of lead from landfill sites.

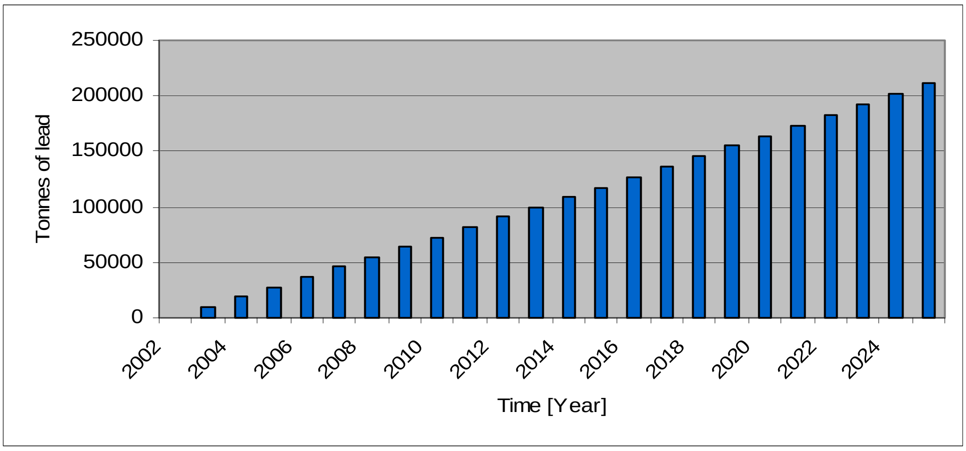

Figure 58: Lead stock in the landfill sites in the NL

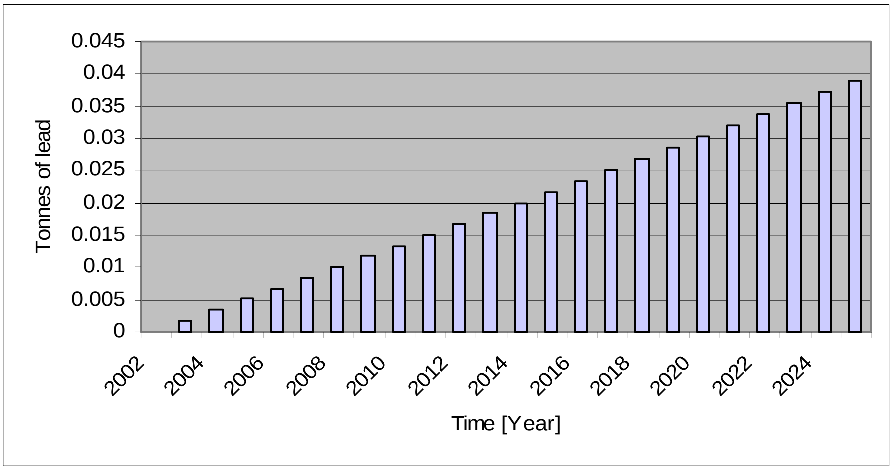

Figure 59: Lead leakage to the water from the stock in the landfill sites in the NL

6.3.5. Recycling processes of lead applications

6.3.5.1. The outflow of lead from the recycling processes

The outflow of lead from the recycling processes is the produced refined secondary lead, lead emissions into air and water and the lead waste flow to landfill sites.

Produced refined secondary lead

The production of secondary lead in the NL from 1980 till 1999 (figure 60) (British Geological Survey, 1980-2000) is known and possible to estimate in the future using regression analysis.

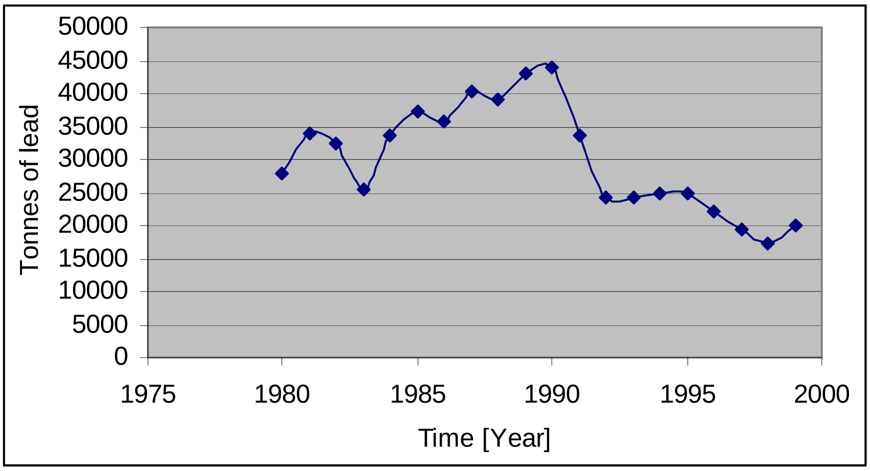

Figure 60: Production of refined secondary lead in the NL in the past

Deriving a model equation of the produced refined secondary lead in the Dutch economy (1980-1999)

The produced refined secondary lead in the NL in the past has been tested with different factors such as per capita GDP, lead price, and the time as a proxy of other variables. The results indicate a negative correlation between per capita GDP and the produced refined secondary lead, significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is low. The correlation with time is similar to the one with the per capita GDP. The correlation with the lead price is not significant and the coefficient of determination (R^2) associated with the correlation is very low. When time and per capita GDP were combined, the coefficient of determination does not change significantly from the one associated with per capita GDP. Therefore, the following model will be used to calculate the production of refined secondary lead in the NL:

*Production of refined secondary lead (t) =43589-(0.07819*GDP/C (t))* (103)

The past and future production of refined secondary lead based on Equation 103 is shown in figure 61.

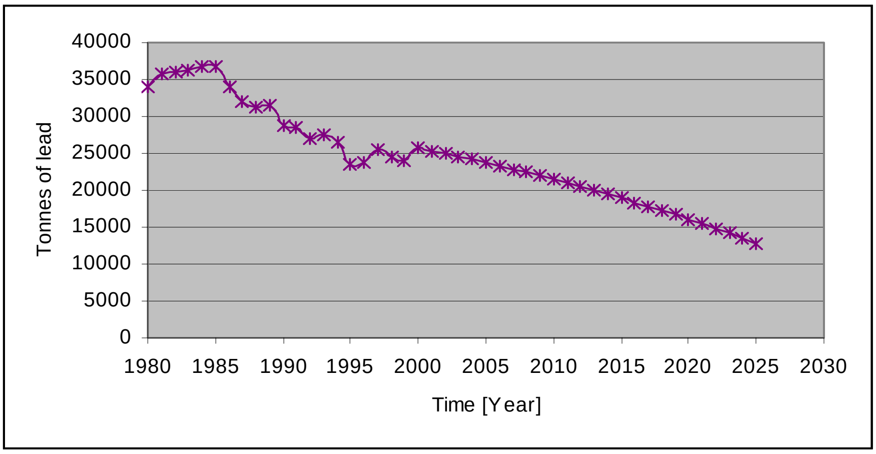

Figure 61: Past and future production of refined secondary lead in the NL

Lead emissions to air

The amount of lead emitted to air during the recycling processes of lead applications is estimated as a fraction of the total produced secondary lead as given by equation 38, where $\alpha_{RE,A}$ in equation 38 is 0.00015 (Thornton et. al., 2001). Figure 62 shows the emissions of lead to air in the past and the future.

Lead emissions to water

The amount of lead emitted to water during the recycling processes of lead applications is estimated as a fraction of the total produced secondary lead as given by equation 38, where $\alpha_{RE,W}$ in equation 38 is 0.00001 (Thornton et. al., 2001). Figure 63 shows the emissions of lead to water in the past and the future.

Lead in the waste stream to be landfilled

The amount of lead ended up in landfills is estimated as a fraction of the total produced secondary lead as given by equation 39, where α_{RL} in equation 39 is 0.00445 (Annema et. al., 1995). Figure 64 shows the total landfilled lead after the recycling processes in the past and the future.

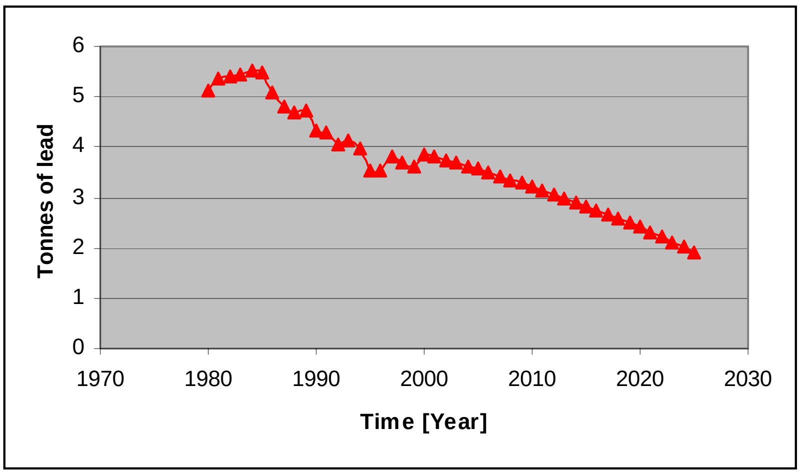

Figure 62: Lead emissions to air during the recycling processes

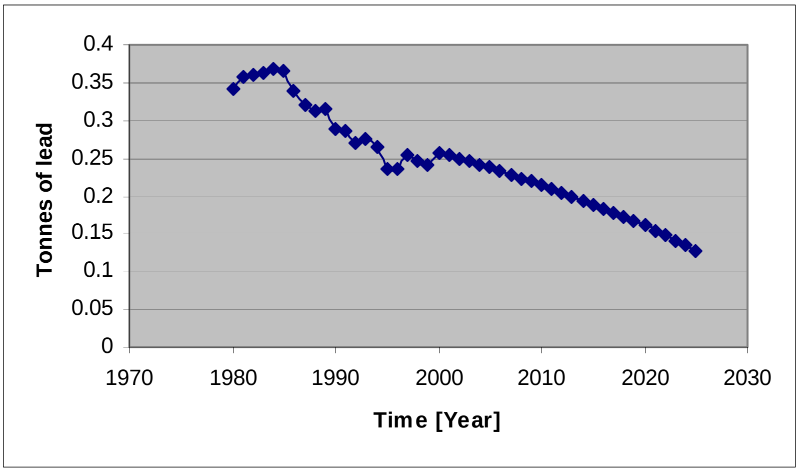

Figure 63: Lead emissions to water during the recycling processes

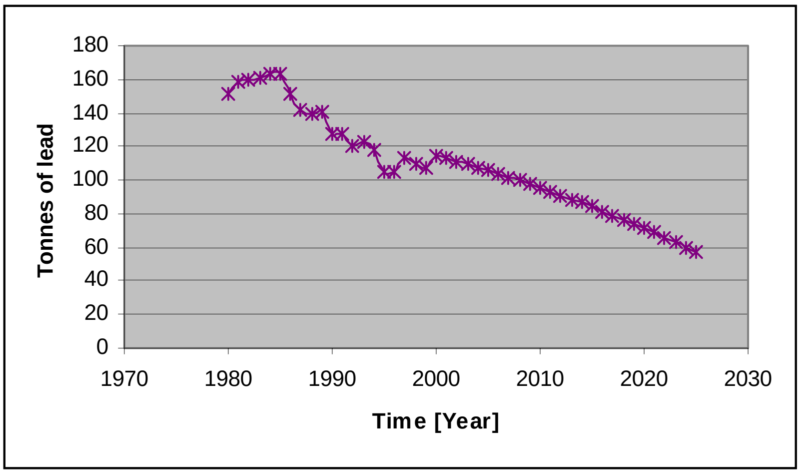

Figure 64: Landfilled lead from the recycling processes

6.3.5.2. Inflow of waste stream of lead containing products into the recycling processes

The inflow of lead to the recycling processes is the amount of lead collected in the NL plus the imported amount of lead minus the exported amount of lead. Due to the difficulties in the estimation of import and export of scrap containing lead, the import and export will be estimated together as net import. The inflow of lead to the recycling processes will be estimated as a balancing item of the recycling processes, equal to the total outflow of lead from the recycling process as given by equation 34. The total outflow of lead from the recycling processes is given by equation 37, and estimated in 6.3.4.1. Figure 65 shows the inflow of lead to the recycling processes.

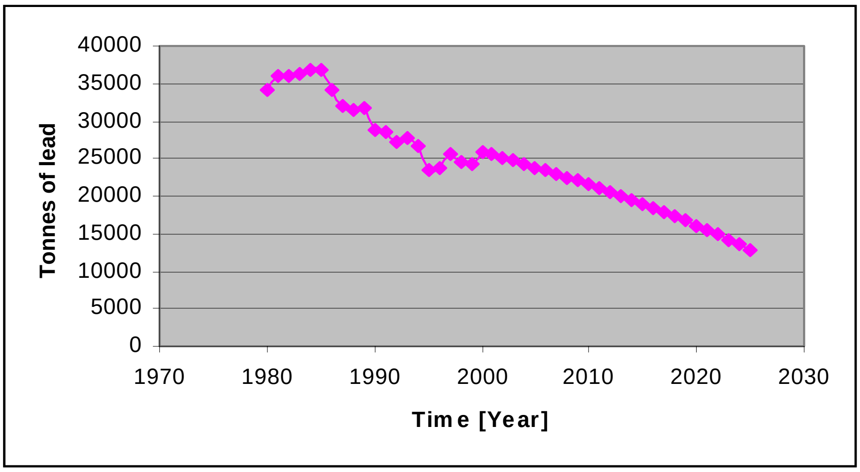

Figure 65: The inflow of lead into the recycling processes

6.4. Net import of refined lead

The net import of refined lead is estimated as the difference between the total inflow of lead into the production processes and the refined lead produced in the NL (primary and secondary). Figure 66 shows the net import of refined lead in the NL in the past and the future.

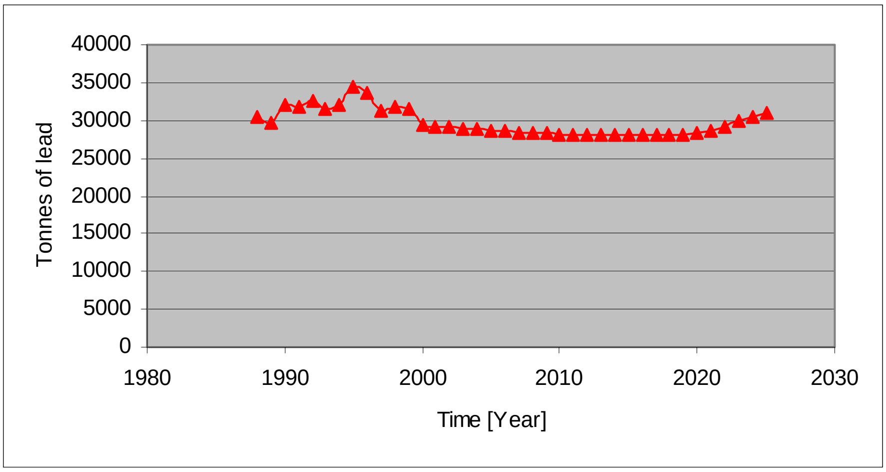

Figure 66: Net import of refined lead in the NL

6.5. Net import of lead scrap

The net import of lead scrap is estimated as the difference between the collected waste stream from the discarded products and the processed waste stream in the region. Figure 67 shows the net import of lead scrap in the future. It is clear that according to the model there is a net export.

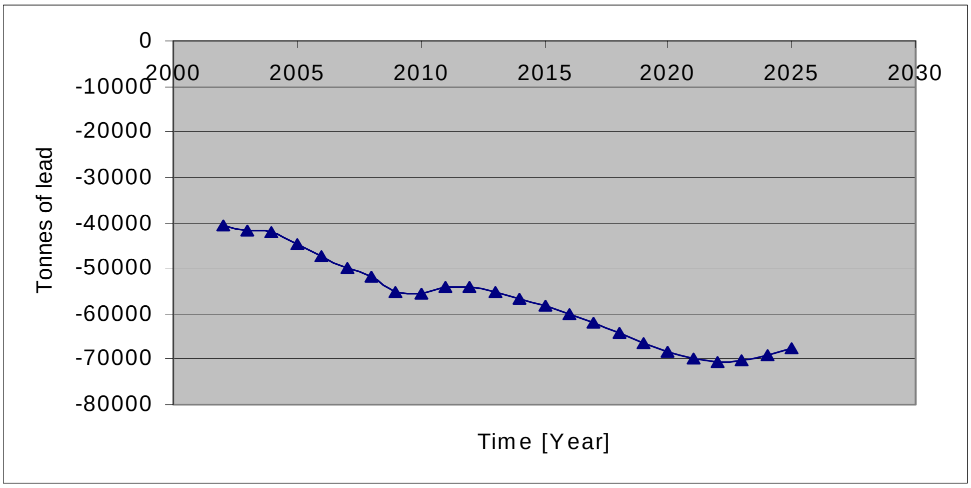

Figure 67: Net import of lead scrap in the NL

6.6. Sewage Sludge

6.6.1. Inflow of lead into sewage treatment

The inflow of lead to sewage treatment originates from the emissions during use, from the consumption of food and animal products and from industrial processes, especially the production of other heavy metals.
The inflow of lead into the sewage treatment from the use phase is estimated as 50% of the total lead emissions during the use phase of lead sheet. The inflow of lead into the sewage treatment from the consumption of food and animal products is estimated as a balancing item in the consumption of food and animal products. The inflow of lead into the sewage treatment from the production of other heavy metals is estimated as 0.106% of the total inflow of lead to the production of other heavy metals through zinc, iron and coal used for steel production. Figure 68 shows the inflow of lead to sewage treatment from different sources.

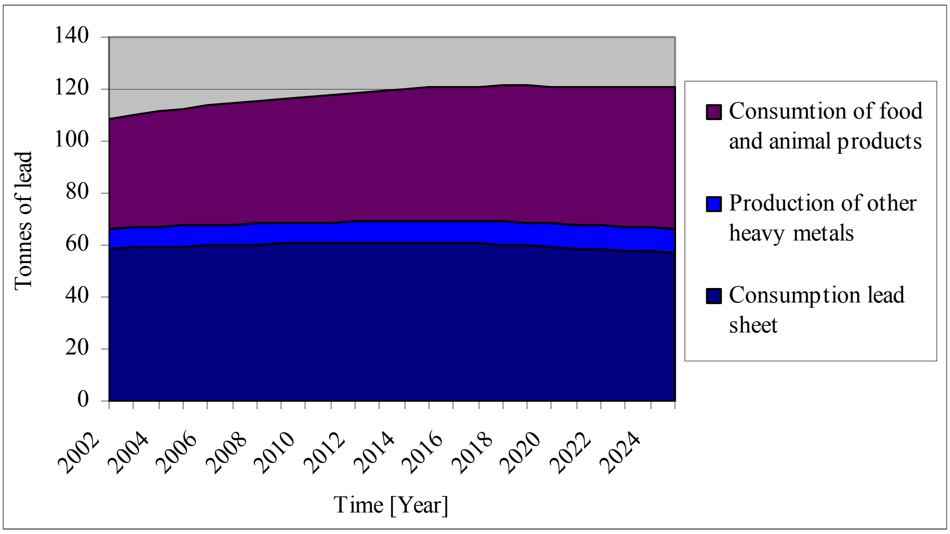

Figure 68: Inflow of lead into sewage treatment from different sources

6.6.2. Outflow of lead from sewage sludge

The outflows from sewage treatment are effluent and sewage sludge. The assumption is that 80% of lead ends up in the sewage sludge and 20% of lead ends up in the effluent. The sludge is distributed over soil, incineration, landfill and other destinations.
The outflows of lead in sewage sludge to soil, to waste incineration and to others are estimated as 15%, 62% and 11% of the total inflow of lead to the sewage sludge (CBS, 2003). The outflow of lead in sewage sludge to landfill sites is estimated as a balancing item of the sewage treatment process. Figure 69 shows the outflow of lead in sewage sludge to soil, incineration landfill sites and others.

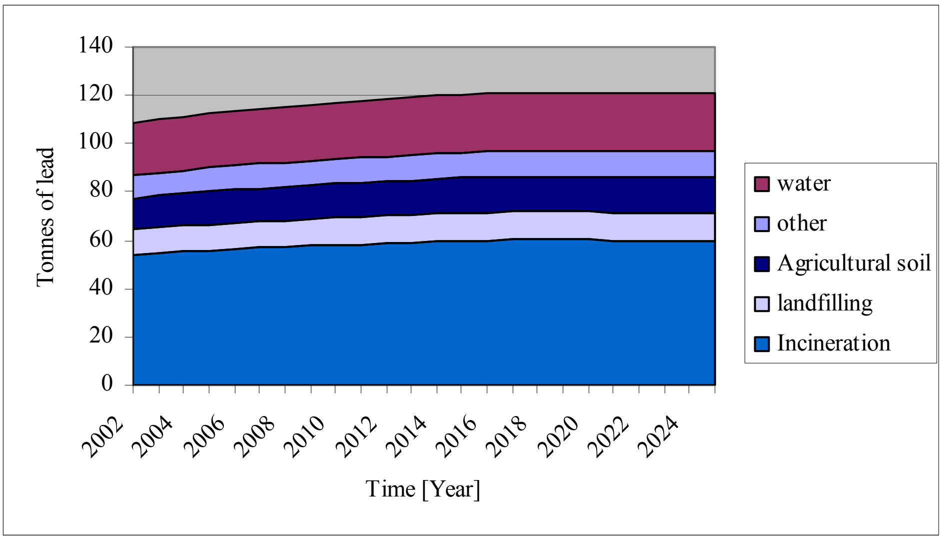

Figure 69: Outflow of lead in sewage sludge to soil, incineration and landfill sites

6.7. Environment system

The main sources of lead flows and stocks in the Dutch environmental compartments (air, water and soil) are the economic activities of lead, whether these activities are related to the intentional use of lead or its non-intentional use. The input of lead to the environmental compartments from the economic activities of the intentional use of lead such as the production of refined lead, and the production, consumption and waste treatment activities of lead containing applications are included in the model. Moreover, the input of lead to the environment as a result of the non-intentional presence of lead in other applications such as phosphate fertilizers, fossil fuel, and other heavy metals ores are also included in the model.
Another important source of lead in the Dutch environmental compartments is the transboundary flows of lead (flows originating from outside the NL). These transboundary flows are not included in the model.
Dutch lead flows and stocks in the environment are also connected to each other, leading to flow from one environmental compartment to another. The model in its present situation accounts for those flows from air to water and soil. Other flows such as the flow of lead from soil to the surface and ground water, the flow of lead from surface water to the sediment and the sea and the dumped flow from sediment are not included.

6.7.1. Air

6.7.1.1. Inflow of lead into air

Lead inflow into air originates from different sources. These are the production of different lead applications, the use of leaded gasoline, the recycling processes of lead scrap, the incineration process, the electricity production from coal, the electricity production from oil, the production of other heavy metals, and the production of oil. Figure 70 shows lead emissions to air from the different sources.

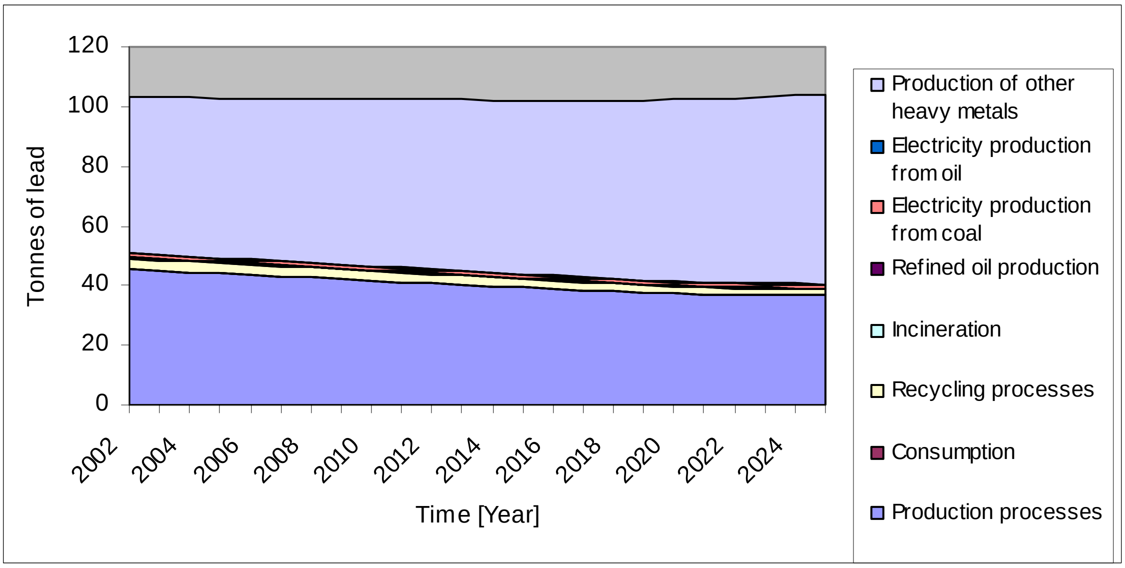

Figure 70: Lead emissions into air from different sources

6.7.1.2. Outflow of lead from air

The outflow of lead from air is the amount of lead deposited in water, agricultural soil, non-agricultural soil, and outside the region. 7% of the total air emissions is assumed to be deposited in water, and 93% of the total air emissions is assumed to be deposited in soil, of which 50% is assumed to be deposited in the agricultural soil and the other 50% in the non-agricultural soil. Figure 71 shows the outflow of lead to the different destinations.

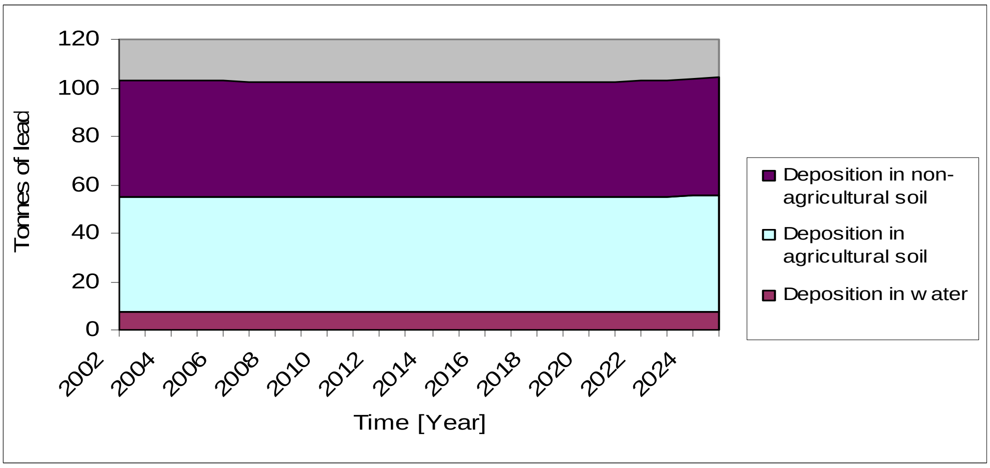

Figure 71: Lead deposited in water, agricultural soil and non agricultural soil in the NL.

6.7.2. Water

6.7.2.1. Inflow of lead into water

Lead inflow into water originates from different sources. These are the recycling processes, the production of different lead applications, the production of other heavy metals, the production of oil, the deposition from air, and the landfill sites. All of these flows are estimated in their respective compartment of origin. Figure 72 shows the inflow of lead into water from the different sources.

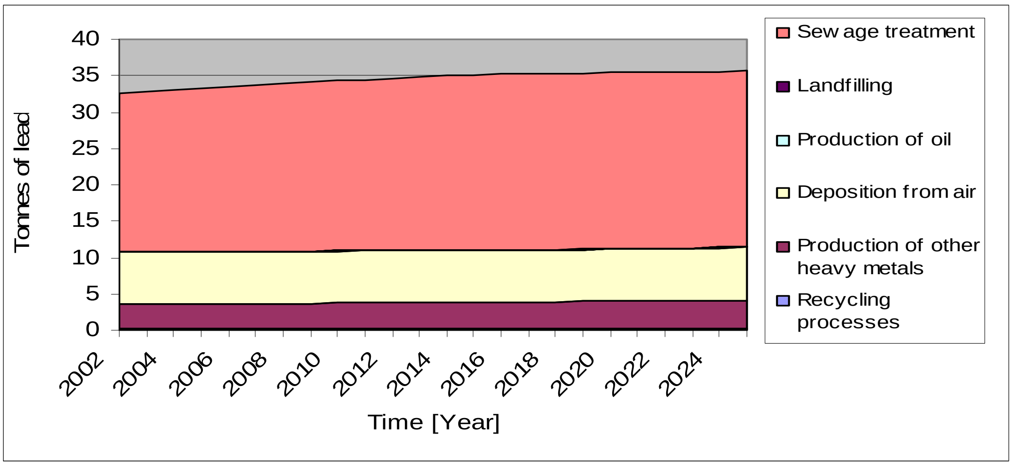

Figure 72: Lead inflow into the water in the NL

6.7.3. Non-agricultural soil

6.7.3.1. Inflow of lead into the non-agricultural soil

Lead inflow to non-agricultural soil originates from different sources. These are the use of different lead applications, the construction materials, the production of oil, and the lead deposited from air. All of these flows are estimated in their respective compartment of origin. Figure 73 shows the inflow of lead into non-agricultural soil.

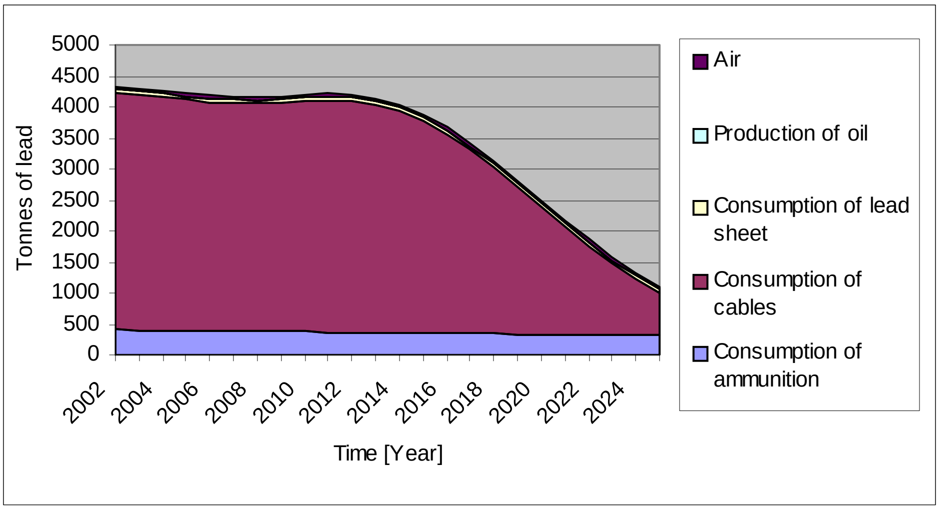

Figure 73: the inflow of lead into the non-agricultural soil in the NL

7 SUMMARY, DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1. The General Dynamic Substance Flow-Stock Model

7.1.1. Summary

The model described in this report is a dynamic substance flow model that consists of several sub-models. Some of these sub-models are related to the economic activities of substances such as the production of substances (primary and/or secondary), the production of products containing these substances, the consumption of these products, the waste management of the discarded products (collection, incineration and landfilling). Others are related to the environmental system such as air, water and soil. The model includes the intentional applications as well as the non-intentional applications of substances, and describes stocks as well as flows.

Each sub-model is connected to several substance flows, and in some cases to one or more stocks. Some of these flows are treated as fixed flows. These flows are estimated based on their development in the past, with regression models that describe these flows as a function of explanatory variables such as GDP, per capita GDP, population growth, population density, world demand for materials and material price.
The same models are used to estimate these flows in the future with projections of the explanatory variables. Alternatively, a specific scenario can be used, if no correlation between the fixed flows and the expected explanatory variables can be found, or if a de-coupling is expected.
Other flows are treated as model relations and estimated on the basis of certain relations with the fixed flows or with each other. The parameters used in the model equations play an important role in determining the accuracy of the model outcome. These parameters may be changing over time and are determined mainly by the developments in the technology or by policy aspects.
The parameters used in these relations are estimated either based on their development in the past and regression models, if a time series of these parameters in the past can be found, or as constants. Alternatively, a specific scenario can be used, if some indications of their developments in the future are available.
In each sub-model, one flow is treated as a balancing item.

The dynamics of the in- and outflow of the substance in the different stages in the economic system are determined by different factors. Some of these factors are related to the developments in the world market and others are related to the developments in the domestic market. Therefore, in addition to the country model, a world model is developed to estimate trends in the demand for the substance and the substance-containing products and serve as a background for the country model.

In the consumption phase, two different types of applications are specified, stock-building applications and short-living applications. Stock building applications are those applications with a life span of more than one year whereas short living applications have a life span equal to or less than one year. For both types of applications, the substance is used either intentionally or non-intentionally.

The domestic demand for the products that contain the substance is considered as the driving force of the consumption phase. The inflow of the substances into the consumption phase is treated as a fixed (time series of) flow(s). For most applications, time series of the past consumption are available. Moreover, it is possible to calculate the two possible outflows (leaching and discarding) as a function of the inflow for the short living applications and as a function of the stock for stock-building applications.
For each product in the consumption phase, the inflow into the consumption phase is modelled based on a regression model that describes the inflow as a function of the socio-economic variables. The socio-economic variables used in the model are GDP, per head GDP, sectoral share in GDP, population growth, and material price.

The outflow of stock-building applications 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 as a result of corrosion, evaporation and suchlike, is modelled as a fraction of the stock-in-use. The delay mechanism refers to the discarding of products after they have outlived their usefulness. This outflow of waste products is modelled as the inflow of some time ago, taking account of the emissions in previous years. Two factors play an important role in determining the accuracy of the outcome of the model, namely the emission factor and the assumption for the product's life span. The emission factors may be changing overtime and are determined by many factors such as the surrounding atmosphere, the weather, maintenance, and others. The product life span is never exactly known, but can be assumed to fit a Weibull distribution or any other distribution depending on the available information.

The outflow of short-living applications out of the consumption phase is the leaching outflow and the discarded products. The emissions during the use of the product are modelled as a fraction of the inflow. The discarded outflow of waste products is modelled as the inflow in the same year minus the emissions during use.

In the waste management phase, three destinations of the discarded products from the consumption phase are specified: recycling, incineration and landfill. The model estimates the end-of-life treatment in the future based on an estimation of the collection rate of discarded products. The incinerated and landfilled flows together then are the difference between the total flow of discarded products and the collected flow. The main driving forces in the waste management phase are the demand for secondary material and policy. These are mainly determining the collection rate.
The collection rate can be modelled based on a regression model that describes the collection rate as a function of the socio-economic variables. The socio-economic variables used in the model are Population density, Per capita GDP, and Landfill tax.
Alternatively, if no time series of the collection rate of products can be found or no correlation between the collection rate and the expected explanatory variables do exist, a specific scenario can be used.
The model estimates the flow to incineration as a fraction of the total not-collected flow of discarded products. The parameter used in this relation is subject to change because of policy, or technical reasons. The flow to landfill is then estimated as the difference between the flow to be incinerated and the total not-collected waste flow.

In the recycling process, different flows are specified. The global demand for the refined substance is the driving force in the recycling stage in the model. The produced refined substance, which is one of the outflows from the recycling plants, is treated as a fixed flow in the model. A time series of the past produced refined substance is possible to find. Moreover, it is possible in many cases to relate the other substance flows to the produced refined substances.
Based on the chosen approach, the future inflow of scrap to the recycling plants within a country can be estimated as a balancing item. Moreover, due to the possibility of estimating the future collected flow in other part of the model (waste management), it is possible to estimate the value of import and export of scrap together as net import of scrap.
The produced refined substance can be modelled based on a regression model that describes this flow as a function of the socio-economic variables. The socio-economic variables used in the model are the global demand for materials, per capita GDP, material price and the time as a proxy of other variable influence.
The other outflows from the recycling processes (air emissions, water emissions and landfilled waste) are estimated as a fraction of the produced refined substance. The parameters used in the model relations in the recycling processes are mainly determined by technical aspects.
Alternatively, these parameters can be estimated as a fraction of the inflow of scrap if a relation between these parameters and the inflow can be found.
The inflow of substance containing scrap into the recycling processes is modelled as a balancing item.

The production phase of substance containing applications is modelled in a similar manner to the recycling processes. The global demand for the applications is the driving force of the production stage.
The outflow of the substances out of the production stage in the produced products is treated as a fixed flow in the model. A time series of the past production of different products usually can be found. Moreover, it is possible in many cases to find a model relation of the other flows with the outflow of the substance in the produced products.
Based on the chosen approach, the future inflow of the refined substance into each production process can be estimated as a balancing item, and so the total inflow of the substance into the production stage can be estimated as the sum of these inflows. Since the amount of primary and secondary production of the substance is known, it is possible to estimate a net import (import minus export) of the refined substance as a balancing item: the difference between demand and domestic supply.

The outflow of the substance in the produced products can be modelled based on a regression model that describes the substance outflow in the produced products as a function of the socio-economic variables. It is important to realize that the outflow out of the production phase does not equal the inflow into the consumption stage. A part of the produced products will be exported. The smaller the country is, the larger will be the disconnection between production and consumption stages. The driving forces for production therefore also are not equal to the driving forces for consumption within the same countries, but rather can be found on the international market. The socio-economic variables used in the model are the global demand for different products, per capita GDP, and the time as a proxy of other variable influence.

The other outflows from the production processes (air emissions, water emissions and landfilld flow) are modelled as model relations. These flows are estimated as a fraction of the outflow of the substance in the produced products. The parameters used in the model relations in the production processes are mainly determined by technical aspects. Alternatively, these parameters can be estimated as a fraction of the inflow of refined substance if a relation between these parameters and the inflow can be found.

No information is needed on the import and export of the refined substance and scrap. In the model, import and export is estimated together as net import based on information from two different sub-models. The net import of the refined substance is estimated based on information from the production of substance containing application and the production of the refined substance. The net import of scrap is estimated based on information from the collection of scrap out of the discarded outflow of the consumption phase and the production of the refined substance.

In general, the environmental sub-models (air, water, and soil) are treated as sinks. Flows and stocks in the environmental compartments are mainly determined by the economic activities and loops and cycles within the environmental system itself. The environmental flows and stocks as a consequence of the substance economic activities are specified and estimated in the economic sub-models. The loops and cycles within the environmental system are not included in details. The substance flow from air to water and soil is estimated based on the country specific area distribution between land and water.

7.1.2. Discussion

The described model consists of several sub-models. These are the production of substances (primary and/or secondary), the production of applications containing these substances, the consumption of applications, and the waste management of discarded applications (collection, incineration and landfilling). The dynamics of the in- and outflow of the substance in these sub-models are determined by separate driving forces, which implies that different explanatory variables will be used in these sub-models.
The disconnection between the different stages is mainly due to the import and export of the refined substance, products containing the substance and scrap, which will be relatively more important when the country is smaller. For a country like the Netherlands the effect of the import and export is crucial. The production of substance containing applications in a specific country is thus disconnected from the consumption of these applications. A similar disconnection can be found between the consumption and processing of scrap, and between the production of the refined substance and its use in the production of products.
The model treats the import and export at different stages in the economic system as a net import to be estimated as a balancing item of two different stages. This implies that the future import and export can not be estimated separately and no analysis of trade can be made which is a limitation of the current model.

The estimates of the future fixed flows are based on regression models that describe the relation between these flows and general explanatory variables such as GDP, per capita GDP, population size and growth, and price. Although these explanatory variables in this case have proven to be the most influential ones, other explanatory variables, which are more case specific, could be also included in the analysis. The only condition is that data on the past development of these variables as well as projections of their future development are available. Other general explanatory variables such as the general consumer price index (CPI) and the CPI for specific products could also be used as explanatory variables. This is especially useful when specific price information is lacking. For the estimates of the future, scenarios for the general CPI are available.

The approach taken to estimate the fixed flows has its advantages and limitations. The advantage of using the regression analysis is the possibility of testing the most significant variable(s) among the socio-economic variables and eliminating those, which do not correlate with the past trend of these flows. The main limitation is the future uncertainty. The basic idea is that the relationship between the fixed flows and the socio-economic variables will remain in future what it has been in the past. This will not be always the case as new developments may occur such as the development of new materials or processes of production, use and waste management, or policy may affect some of these flows in the future in different ways of those in the past. Changes like that will render the fixed flows equations useless. Some of these factors, however, can be included in specific scenarios for the future development.

Another possible approach would be to define a general model beforehand, built up out of the variables that one assumes to be important combined in a manner that one assumes to be relevant. For such an approach, however, a certain prior knowledge or insight in the system and the relations within is required.

For model relations, several possibilities are proposed. If a time series of the past can be found, the relation can be estimated based on regression analysis. In this case, the advantages and limitations of the use of regression analysis are the same as those mentioned above. If a time series of the past cannot be found, there are two possibilities. If some qualitative information regarding the relation is available, a scenario can be developed. In this case, the model outcome will be conditioned. Otherwise, the past relation can be assumed to be valid for the future.

The environmental compartments in the model are limited to the air, water, and non-agricultural soil. Although the agricultural soil is an environmental compartment, it is treated in the model as part of the economic system because it is used as a mean of production. The landfill sites is also treated as part of the economic system since it is under human control. For the modeling, this choice will not make any difference.

The environmental sub-models are treated as a sink in the model. Loops and cycles within the environmental system are not included in details. This implies that the environmental system is not modelled adequately and the outcome of the model regarding the environmental compartments should not be treated as final. The emphasis in this model was mainly on the economic system. It is possible, however, to include the environmental system in more details but more data need to be collected.

The dynamic substance flow model presented in this report, like many environmental or economic models, has several sources of uncertainty. The uncertainties in the model are due to many sources related to the different sub-models in the system. Some of these are related to equations used to model the fixed flows, others are related to the parameters and mathematical formulas used in the model relations.

7.1.3. Conclusions

The model developed and presented in this report is a dynamic substance flow analysis model that combines substance stocks and flows in the economic and environmental systems. The substance stock model describes the direct inflows into and outflows out of the stock over time. Substance flow models describe the inflows into and outflows out of a specific process in one year. The developed model integrates both, based on (1) expressing the flows in and out of the stock in yearly flows and specifying the stock's size per year and (2) specifying the flows which are not linked to the stock over time to cover the same time period. The model includes both the intentional use and non-intentional use of the substance in the economy and the environment.

- Integrating substance flow and stock models will lead to better estimates of several future flows, especially waste flows. These flows are connected directly to the discarded outflow from the stock. Such stocks are usually ignored in forecasts. Emissions to the environment sometimes also originate form stocks. Including them may therefore lead to better forecasts of emissions. The sources of the problematic environmental flows can be determined and compared, thereby also giving insight in the relative importance of stocks for future environmental problems.

- The developed model gives a complete picture of the economic system. It includes the intentional and non-intentional applications of the substance in the different economic activities, therefore the environmental consequences of both types of applications can be estimated and compared.
- The developed model contains both socio-economic mechanisms and mass balances. It specifies the flows in three categories: flows with fixed values, flows estimated as model relations and flows estimated as balancing items. The fixed flows have known values in the past. In the model, the estimates of their values in the future are determined by regression analysis. Flows can also be estimated from their relation with other flows in the system. In the model, the estimates of their future values are based on either determining the main factors effecting the dynamics of this relation or on the assumption that the past relation is valid in the future. Finally flows can be estimated by applying the material balance to a specific process knowing all other flows connected to this process. In the model, the estimates of their future values are also determined by applying the material balance.

- The developed model is based mainly on economic driving forces. The driving force for the primary and/or secondary production of the substance is the demand for this substance. The driving force in the production of products containing the substance is the demand for these products. The driving force for the consumption phase is the domestic demand for products. The main driving forces in the waste management stage are the demand for secondary material and policies on waste. These are mainly determining the collection rate. The driving force for the production and consumption of the non-intentional applications is the demand for these applications. Different factors or explanatory variables determine the dynamics of each driving force. Regression analysis is used to determine the most influential factors on these driving forces. The equations derived from the regression analysis are used to estimate the future values of these flows using certain scenarios for the future development of these factors.

- The model can be used not only to evaluate the environmental impact of the use of substances, but also to estimate the possible future availability of resources and the future demand of the substance and substance containing applications. This is important information for the future management of resources.

- The developed model has been applied to the case of lead flows and stocks in the Netherlands. The lead model includes most of the intentional applications of lead, such as batteries, lead sheet, cathode ray tubes, cable sheathings, ammunition and leaded gasoline which constitute the largest part of lead use in the economic processes. It also includes some of the non-intentional applications such as the existence of lead as a contaminant in other heavy metals, fossil fuels and the agricultural sector. Moreover, the model includes the environmental compartments (air, water and soil) and treats them as sinks.

7.2. The Lead Flow-Stock Model

7.2.1. Summary

The developed model has been applied to the case of lead flows and stocks in the Netherlands. In the model, some lead flows are treated as fixed flows. These are
- the inflow of lead into the consumption phase,
- the outflow of refined lead from the recycling processes,
- the outflow of lead in lead containing applications from the production processes,
- the inflow of lead due to the production of other heavy metals (zinc, iron and steel),
- the inflow of lead due to the use of phosphate fertilizers, and
- the inflow of lead due to the use of coal and oil in electricity production and the production of oil.

Other lead flows are estimated as balancing items. These are
- the discarded outflow of lead from the consumption phase,
- lead flow to be incinerated and landfilled together in the waste management,
- the inflow of lead scrap into the recycling processes,
- the inflow of refined lead into the production of lead containing applications,
- the net import of lead scrap as a balancing item of the scrap market,
- the net import of refined lead as a balancing item of the refined lead market,
- lead flow to be landfilled from bottom and fly ash,
- lead flow to be landfilled from sewage sludge,
- the discarded outflow from construction material,
- lead emissions from oil used for electricity production.

All other flows are estimated as model relations such as
- the emissions during production of refined substances, the production of substance containing applications, the consumption of these applications, and the incineration process,
- the emissions during the production of other heavy metals and the use of coal and oil for electricity productions,

- lead outflow from the production of other heavy metals to be landfilled, to be utilized in asphalt and to the sewage sludge,
- the utilized flow of lead from bottom and fly ash

The total lead demand is modelled on the basis of the demand of its individual applications in the consumption phase. The demand for SLI batteries is expected to decrease and then stabilize, however, the demand for both industrial and traction batteries is expected to increase slightly. The demand for lead sheet is expected to stabilize in the future. The demand for computer monitors CRT's is expected to increase in the future, however, the demand for televisions CRT's is expected to stabilize. The demand for ammunition is expected to decrease and the demand for leaded gasoline will be zero due to the phase out policy.
The inflow of lead into the Dutch economy as a consequence of its existence as a contaminant in other applications is modelled on the basis of the demand for these applications. The demand for phosphate fertilizers is expected to decrease due to the policy in the NL.
Although the share of coal and oil in the total electricity production is decreasing, the demand for fossil fuels (coal and oil) for electricity production is expected to increase.
The production of other heavy metals (zinc, iron and steel) is expected to increase.

The collection rates for lead containing applications are modelled either on the basis of explanatory variables when time series for the past collection rate are available or on the basis of certain scenarios.
The collection rate of lead sheet is expected to increase and it will stabilize at 100% from 2003 onwards. The collection rates for the other applications are assumed either to increase overtime if there is indication that this would be the case in the future due to for example policy or remain as it was in the past when no such information is available. The collection rate of SLI and traction batteries is expected to increase by 0.5% every year. The collection rate of industrial batteries is stable at 100%. The collection rate of CRTs is expected to increase by 1% every year. The collection rates of cable sheathing, small vehicle applications and ammunition are expected to be the same as in the past.
In the future, the largest contribution to lead recycling is made by lead sheets followed by SLI batteries. Smaller contributions are made by other batteries and cable sheathings.

The largest flow to the incineration plants from the discarded waste stream from the consumption phase in the past is related to SLI batteries. In the future, this flow is expected to be zero due to the increasing collection rate.
Other flows also contribute to the total incineration of lead. These are traction batteries, lead sheet, small vehicle applications and CRTs. In the future, the flow of lead sheet and traction batteries to be incinerated is expected to be zero because the collection rate is assumed to reach 100%. The flows of small vehicle applications and of CRTs to be incinerated are expected to increase in the future.
The flow of lead from sewage sludge to be incinerated is expected to increase till 2019 and then start decreasing. The lead flow from sewage sludge to be incinerated is small compared to the flow of lead from the discarded waste stream from the consumption phase.

Similar to the incineration of lead containing applications, the largest flow to the landfill sites from the discarded waste stream from the consumption phase in the past is related

to SLI batteries. In the future, this flow is expected to be zero. Other flows also contribute to the total landfilling of lead. These are traction batteries, lead sheet, small vehicle applications and CRTs. In the future, the flow of lead sheet and traction batteries to be landfilled is expected to be zero but the flows of small vehicle applications and of CRTs are expected to increase.
In addition to the flow of waste stream from the consumption phase, several other lead flows contribute to the availability of lead in the landfill sites, namely: lead flow from the recycling processes, lead flow from sewage sludge, lead flow from the production of other heavy metals and lead flow in landfilled bottom and fly ash. By far the largest flow to landfill sites is the lead flow from the production of other heavy metals, followed by the lead from the waste stream from the consumption phase. The lead flows from the recycling processes, sewage sludge and lead flow in the landfilled bottom and fly ash are very small compared to lead flow from the discarded waste stream from the consumption phase and lead flow from the production of other heavy metals.

The recycling of the scrap of lead containing applications in the Netherlands is decreasing overtime. In the future, the recycling of lead containing applications scrap is expected to continue decreasing.

The total lead demand in the production processes of lead containing applications is modelled on the basis of the production of its individual applications. The production of some applications in the Netherlands such as SLI, traction and industrial batteries is expected to increase over time. The production of other applications such as lead sheet, CRTs, small vehicle applications, gasoline and the other applications is expected to decrease overtime. Although the production of some applications is expected to increase, the overall amount of lead in the produced products in the Dutch economy is expected to decrease. The production of ammunition is expected to decrease overtime as the total production of lead containing products is expected to decrease.

Although the demand for refined lead in the production of lead containing applications is expected to decrease in the future, the supply of refined lead from the Dutch recycling industry will not be enough to meet the demand. This is because the production of refined lead in the Dutch economy is decreasing at a higher rate than the production of lead containing applications. Therefore the net import of refined lead has an increasing positive value.
On the contrary, the net import of lead scrap has a negative value because the collected waste stream is increasing over time while the processed lead scrap in the NL is decreasing.

Flows and stocks in the environmental system interact with economic flows and stocks and with each other. In the model, those flows and stocks resulting from the processes in the economic system are included. Other flows and stocks that result from the loops and cycles within the environmental system itself are not treated in details.

The inflow of lead into the air originates from different sources in the economic system. The largest lead flow emitted to the air originates from the production of other heavy metals. In the future, lead emissions to the air during the production of other heavy metals are expected to increase. The second largest flow originates from the production of lead containing applications. In the future, lead emissions to the air during the production processes of lead containing applications are expected to decrease as the

production of different lead applications is decreasing. Lead flows to the air from other sources such as the electricity production from coal and oil, the production of oil, the incineration plants and the consumption of lead containing applications is small compared to the two flows mentioned above. In general, the total lead emissions to the air are expected to stabilize since one of the main contributors is increasing in size, while the other one is decreasing.
The inflow of lead into surface water originates from different sources in the economic and environmental systems, the largest of which is the effluent from sewage treatment plants followed by atmospheric deposition. In the future the inflow of lead from sewage treatment plants is expected to increase and the deposition of lead from air into the water is expected to be stable. The third largest flow originates from the production of other heavy metals. In the future, lead emissions to the water during the production of other heavy metals is expected to increase. There is a small amount of lead emitted to the water originating from the recycling processes and the production of oil.

The lead inflow into the soil originates from different sources in the economic and the environmental system, the largest of which is due to the consumption of cables. In the future, lead in soil originating from the consumption of cables is expected to decrease. The second largest lead flow to the soil originates from the use of ammunition: bullets for hunting and sporting. This flow is also expected to decrease in the future. There is a small contribution to lead in soil from the air, the corrosion from lead sheet, and the production of oil.

7.2.2. Discussion

Different explanatory variables are used to model the fixed flows. The expected influential explanatory variables appeared to be sufficient to explain some of these flows such as past inflow of lead to the consumption phase, the past production of refined lead, the past production of other heavy metals, and the past production of oil and its use for electricity production. The explanatory variables appeared to be insufficient to describe the past production of lead containing applications, the inflow of phosphate fertilizers and the production of electricity from coal. Therefore, the time is used as a proxy of the effect of other influential variables to model the production of lead containing applications and the inflow of fertilizers.

In the case of fertilizers, other explanatory variables such as the number of animals and the agricultural yield could also be used in the analysis, however, these variables are not used in the Dutch case as it is clear that the most influential variables are related to the policy.

Although the past use of coal for electricity production could not be explained by the explanatory variables directly, the explanatory variables are sufficient to describe the total electricity production and the production of electricity from other sources, thus it was possible to estimate the production of electricity from coal.

A time series on the waste treatment of the different lead applications was difficult to find, except for the collection of lead sheet in buildings. Therefore, specific scenarios were used to model the parameters used in the estimates of the collected, incinerated and landfilled flows.

Time series of the past development of the collection rate of lead sheet used in buildings could be found and the explanatory variables appeared to be sufficient to describe it. For other applications different scenarios are used. The collection rates of SLI batteries, traction batteries and CRTs are assumed to increase over time as a result of policy. The collection rate of industrial batteries, cables, small vehicle applications and ammunition are assumed to be constant.

The parameters used in the model relations of the estimates of air emissions flows, water emissions flows, landfilled flows, and others in different parts of the economic system are subject to change as a result of the technical developments. To model these parameters, information on their past development should be known. For lead, it was difficult to find such information. Therefore, these parameters are estimated as a fraction of the known flows by linear coefficients.

Different assumptions have been made regarding the initial stocks of different stock-building lead applications in the consumption phase and lead in landfill sites.
The initial stocks of different lead applications in the consumption phase are estimated based on the availability of these applications in a specific year, which is used as a starting year for the calculation. For the future, these stocks will not affect the outcome of the model if the difference between the starting year of the past inflow and the starting year of the future calculation is more than the application's life span.
The initial stock of lead in the landfill sites is difficult to find. In the model, the initial stock of lead in landfill sites is assumed to be zero. This assumption will affect the estimates of the future stock and the outflow of lead from landfill sites, which will be underestimated.

The result of the model shows that the amount of lead available for recycling is expected to become larger than the demand for lead in the near future. This means that at least in the Netherlands the demand can be met by the supply of secondary lead only. If likewise developments can be found in other countries, it may have consequences on the price of lead and thus also on the profitability of primary production as well as the recycling industry. Consequently, this might increase the landfilling and incineration on the expense of recycling and ultimately an increase in the emissions.
The discarded outflow of lead containing applications from the consumption phase is estimated based on the product life span. The product life span is assumed to fit a weibull distribution. However, other types of distributions can be used.

Another model result is that the environmental consequences of the non-intentional use of lead are considerable compared to those of the intentional use of lead especially those related to the production of other heavy metals (zinc, iron and steel). This result is mainly based on parameters that are assumed to be constant. In reality these parameters are subject to changes due to technological developments.

7.2.3. Conclusions

The dynamic substance flow-stock model has been applied to the case of lead in the NL. The lead model includes most of the intentional applications of lead, such as batteries, lead sheet, cathode ray tubes, cable sheathings, ammunition and leaded gasoline which constitute the largest part of lead use in the economic processes. It also includes some of the non-intentional applications such as lead as a contaminant in other heavy metals, fossil fuel and the agricultural sector. Moreover, the model includes the environmental compartments (air, water and soil) and treats them as sinks. The main conclusions regarding the lead model are:

- Although the demand for some lead intentional applications is increasing, the inflow of lead into the Dutch economy through its intentional applications is expected to decrease. Meanwhile the inflow of lead into the Dutch economy is expected to increase as a consequence of its existence as a contaminant in other applications such as phosphate fertilizers, electricity production from fossil fuel (coal and oil) and the production of other heavy metals (zinc, iron and steel). This is due to the increasing demand for electricity and other heavy metals.

- The discarded outflow of lead from the consumption phase is expected to increase due to the old stock resulting from the extensive use of lead in the past. The availability of lead for recycling will exceed the demand for lead (primary and secondary) in the NL due to an increase in the discarded outflow and the collection rates of lead applications and a decrease in their demand.

- The estimates of import and export of scrap, refined substances, and produced products are output of the model rather than input to the model. The outcome of the model suggests that the Netherlands is a net import of refined lead and net export of lead containing scrap.

- Stock related waste flow to be landfilled is small compared to the flow related waste. This is mainly due to the production of other heavy metals.

- Stock related emissions to the air and water are very small compared to the flow related emissions. This is mainly due to the emissions from the production of lead intentional applications and the production of other heavy metals. Stock related emissions to the non-agricultural soil are very large compared to the flow related emissions. This is mainly due to the consumption of cables in the past.

- The outcome of the model suggests that the environmental consequences of the non-intentional use of lead are considerable compared to those of the intentional use of lead.

- The main sources of uncertainty in the lead model are due to the assumptions made in the estimates of the model relations, the estimates of the initial stocks and the future uncertainty in the equations used for the fixed flows.

7.3. Recommendations

The model in its current situation has some limitations. This is mainly due to the fact that not everything is included and to the nature of the uncertainties that are always connected to this type of models. Therefore, some of the most important aspects that need more investigation and detailed analysis are pointed out below:

- In most cases, the parameters used in the model relations are estimated by linear relations and the past relation is assumed to be valid for the future, however, these parameters are subject to change mainly due to developments in technologies. It is necessary to investigate these trends and parameters in more details.

- Different explanatory variables are used in the model, however, some explanatory variables are excluded due to data availability. It is important to find data sources or indicators for these explanatory variables.

- For the lead case study, the model includes lead flows and stocks in the economic system and the environmental flows and stocks, which are directly linked to the economic activities. Lead transboundary flows and the loops and cycles within the environmental system are not included. To have a complete picture of the environmental flows and stocks, it is necessary to include these flows and stocks.

- As was discussed above, there are many sources of uncertainty in the model. A complete and comprehensive sensitivity and uncertainty analysis is recommended to make statements about the value and limitations of the model outcomes, and to establish the boundaries and conditions for drawing policy relevant conclusions from these outcomes.

- The model has been applied to the lead case. It is important, however, to implement the model to other case studies to explore all possibilities.

- The model can be used for both the management of resources and pollution problems. The policy relevance of the model needs to be explored.

- The model includes both socio-economic and physical aspects. It is important to investigate the possibilities of linking the model to the IOA, environmental models, and economic models.

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APPENDIX A - DATA USED IN THE LEAD MODEL

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APPENDIX B – LEAD MODEL EQUATIONS AND PARAMETERS

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APPENDIX C – THE ANALYSIS OF THE FIXED FLOWS IN THE LEAD MODEL

C.1 Analysis of the inflow of zinc (1980-2000)

Variable	B_0(t-value)	B_1 (t-value)	β_2 (t-value)		R^2	F-statistics
Population	-87610(-1.6)	0.01947(5.5)			0.62	31.3
GDP	178998(28.2)	9.54E-9(4.2)			0.48	18.0
Per capita GDP	177161(25.7)	0.15521(4.1)			0.47	17.2
Price	175418(13.9)	25.2351(2.3)			0.22	5.5
Pop, GDP	-293577(1.8)	0.03478(3.0)	-8.87E-9(1.3)		0.65	17.3
GDP, price	169363(16.5)	8.29E-9(3.3)	11.3575(1.1)		0.52	9.9
Pop, GDP, price	-293880(1.9)	0.03416(3.0)	-9.69E-9(1.5)	10.341(1.29)	0.68	12.6
Pop, price	-71204(1.3)	0.01768(4.6)	9.12402(1.1)		0.64	16.4

C.2 Analysis of the inflow of iron (1990-2000)

Variable	B_0(t-value)	B_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-3.06E6(-0.5)	0.54053(1.5)		0.2	2.3
GDP	3.27E6(4.4)	5.78E-7(2.7)		0.45	7.5
Per capita GDP	2.94E6(3.5)	10.4078(2.8)		0.47	8.2
Pop, GDP	8.12E6(1.1)	-0.3627(-0.6)	7.92E7(2.07)	0.48	3.7

C.3 Analysis of the inflow of steel (1990-2000)

Variable	B_0(t-value)	B_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-7.85E6(1.1)	0.89512(2.0)		0.32	4.3
GDP	2.95E6(3.4)	8.64E-7(3.5)		0.58	12.5
Per capita GDP	2.5E6(2.6)	15.3636(3.6)		0.59	13.2
Pop, GDP	6.65E6(0.79)	-0.2767(-0.4)	1.03E-6(2.2)	0.59	5.8

C.4 Analysis of the total electricity production (1990-1998)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-3.11E5(-7.5)	2.55E-2(9.5)		0.92	91.1
GDP	39853(3.9)	1.18E-8(4.0)		0.7	16.5
Per capita GDP	36724(3.0)	0.196(3.6)		0.65	13.1
Pop, GDP	-337170(-3.9)	0.02744(4.4)	-1.19E-9(-0.3)	0.93	39.9

C.5 Analysis of the electricity production from gas, nuclear and other sources (1990-1998)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-308054(-5.2)	0.02351(6.1)		0.84	37.4
GDP	19490(1.5)	9.86E-9(2.7)		0.51	7.5
Per capita GDP	17465(1.1)	0.16059(2.4)		0.46	6.1
Pop, GDP	-445462(-4.2)	0.03384(4.3)	-6.21E-9(-1.5)	0.88	23.2

C.6 Analysis of the electricity production from oil (1990-1998)

Variable	B_0(t-value)	B_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-9869(-1.5)	8.65E-4(2.0)		0.37	4.2
GDP	1277(2.3)	6.25E-10(3.9)		0.68	15.5
Per capita GDP	986.53(1.6)	0.01092(4.1)		0.71	17.3
Pop, GDP	12700(1.5)	-8.31E-4(-1.3)	1.02E-9(3.1)	0.76	9.6

C.7 Analysis of the production of refined oil (1985-1998)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	-125323(-5.9)	0.01173(8.4)		0.85	71.0
GDP	35547(18.6)	5.63E-9(8.9)		0.86	79.4
Per capita GDP	34286(16.5)	0.09212(8.7)		0.86	76.8
Pop, GDP	-29504(-0.4)	0.00472(0.9)	3.46E-9(1.44)	0.87	39.8

C.8 Analysis of the inflow of phosphate fertilizer (1961-2000)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Population	272694(22.6)	-0.013(-15.5)		0.86	241
GDP	106568(62.4)	-1.2E-7(-14.9)		0.85	224
Per capita GDP	107936(62.4)	-1.93(-15.4)		0.86	237
Population G	47552(6.5)	0.351(5.5)		0.45	30
Price	174785(21.8)	-195(-11.0)		0.81	122
Time	114932(57.2)	-1386(-16.2)		0.87	263
Time, PopG	114075(16.4)	-1375(-11.2)	0.005(0.13)	0.87	128

C.9 Analysis of the lead sheet collection rate (1993-1999)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
PopD	-289.4(-2.77)	0.826(3.6)		0.68	13.1
GDP/C	25.2(1.15)	0.00027(2.9)		0.58	8.6
PopD, GDP/C	-234.2(-3.5)	0.612(3.9)	0.00018(3.3)	0.90	22.66

C.10 Analysis of the production of refined lead in the NL (1980-1999)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
GDP/C	43589(9.4)	-0.078(-3.1)		0.34	9.4
Price	26391(3.5)	3.69(0.5)		0.015	0.27
Time	38555(12.1)	-797.2(-3.0)		0.33	9.0
World demand	42099(6.5)	-0.059-0.64)		0.015	0.28
GDP/C, Time	42099(6.5)	-0.05(-0.64)	-288.7(-0.34)	0.34	4.5