Development of a dynamic model for Substance Flow Analysis:
Part 1 – General stock model

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Study funded by Vito

2004/IMS/R/292

December 2004

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1 INTRODUCTION

The extraction, use and discarding of materials gives rise to environmental problems. Some of these problems are related to resource depletion, others to pollution resulting from emissions during the life cycle of these materials. Forecasting future waste streams and emissions is useful for environmental policy. Scenario analyses and environmental forecasts are conducted to obtain a picture of future developments and their consequences for environmental problems.

Environmental models are suitable to estimate the environmental consequences of emissions. Estimating the future emissions themselves is another matter. In practice, this is often done by using economically oriented models. However, these models usually ignore physical laws, such as mass balance and stock building over time. The predictions from these models blindly follow economic forecasts, at best based on growth forecasts for different economic sectors. In some cases, this works out fine, but in others it leads to sometimes wildly erratic predictions. Another way to predict future emissions is to use material flow models. These models capture some aspects a lot better, but on the other hand are limited to physical considerations and ignore economic mechanisms of supply and demand. These models have no rationale for predicting any future developments, other than applying mass balance. To obtain more accurate predictions, elements from both types of models should be combined. This is the subject of the present report.

This study can be placed in the field of Industrial Ecology, a relatively new field of research. Industrial Ecology studies society's metabolism to analyse the causes of the environmental problems and indicate possibilities for a more sustainable management of materials. Substance flow analysis (SFA) is one of the main analytical tools within the Industrial Ecology research field. SFA is used to describe or analyse the flows of one substance (group) in, out and through a system (Voet, 1996). The system is a physical entity, often representing a geographical area. In most cases, the SFA system is divided into two subsystems: the economic or societal subsystem and the environmental subsystem. SFA is based on the materials balance principle, which enables different types of analysis. Substance flow accounts can be used to identify major flows and accumulations and, if available for several years, to spot trends. Static SFA models can be used to identify causes of pollution problems and to assess the effectiveness of measures.

Recently, it is acknowledged that the main difference between static and dynamic models in SFA lies in the inclusion of stocks in society (Bergbäck, and Lohm, 1997). Stocks of products and materials in use are a major cause of disconnection between the system's inflow and its outflow in one year. This is due to the fact that chemicals sometimes have a long residence time in society, when they are locked in applications with a long life-span such as building materials or durable user goods. The dynamics of such stocks are very important for the generation of future waste and emissions, but so far are no part of models, not even of MFA or SFA models, and consequently are left out of environmental forecasts altogether.

The value added of dynamic SFA models lays mainly in the possibility to predict future emissions and waste streams from built-up stocks in society. These emissions can be considerable and even dwarf the directly production- and consumption related emissions. Examples are:

- Future world-wide emissions of CFCs from present stocks in society will be in the same order of magnitude as the accumulated past emissions, even when a complete phase-out is assumed (Kleijn & Van der Voet, 1998);
- Emissions of heavy metals have decreased over the past decades at the expense of a stock increase. Due to this increase emissions may rise again in the future (Bergbäck & Lohm, 1997; Guinée et al., 1999; Obernosterer et al., 1998).

From such examples it appears that a stock management is required to control emissions on the long run. Dynamic SFA therefore provides relevant information for a strategic environmental policy.

Our main objective in this study is to develop a general dynamic substance stock model that combines elements from both the physical models and the economic models in order to estimate the current and future waste streams and emissions. The approach used basically consists of three steps: (1) model the inflow into the substance stock (newly produced products wherein the substance is applied), (2) model the stocks outflow (discarded products and emissions during use), and (3) model the stock itself (products-in-use). To obtain a really dynamic model for Substance Flow Analysis, the stock model must be integrated into a flow model. This integration is not a part of this report, but will be the subject of later studies.

The starting points of the investigations concerning the stock model are the following:

- We assume that the inflow into the stock of products-in-use is determined by the demand for these products.
- We assume that the outflow out of the stocks depends on two basic mechanisms: *delay* and *leaching*. Delay represents the discarding of products and is determined by the life span of the products. Leaching refers to the emissions of the substance from the products during the use process.
- The change of the magnitude of the stock over time is a result of the difference between the inflows and the outflows over time.

In chapter 2, the stock model and the most important factors affecting the stock dynamics will be described. Chapter 3 will outline modelling approach for estimating the stocks inflows and outflows. In chapter 4, the sources of uncertainties for the stock model will be described and some possibilities for treating them will be discussed. Chapters 5 and 6 describe the application of the stock model to the case of lead in the EU and the Netherlands. Chapter 7, finally, contains a general discussion, conclusions and recommendations.

2 GENERAL DESCRIPTION OF THE ECONOMIC SYSTEM AND ITS COMPONENTS

Within the community of systems analysis, there are many interpretations of what a system is. In general, ‘system’ is a term, which can be applied to a vast number of different things and can be defined as a group of interacting, interrelated or interdependent elements forming a complex entity. Each element has specific properties that enable the system to function. A system can be a physical entity, a social entity, or an abstract idea, and can be either an open or closed system.

In Substance Flow Analysis (SFA), the system is a physical entity: a coherent set of elements determining the flows of a certain substance or group of substances. Generally, the SFA system represents a geographically demarcated area: a country, a region, a group of countries, or even the whole world. In most cases, the SFA system is divided in two subsystems, the economic and the environmental subsystem. The economic subsystem is also called ‘societal subsystem’, ‘technosphere’ – indicating that the system is not concerned with financial aspects – or ‘anthroposphere’. In this section, the economic subsystem (figure 2.1), its main components, its main variables and parameters, and the most important aspects affecting its dynamic behaviour will be discussed.

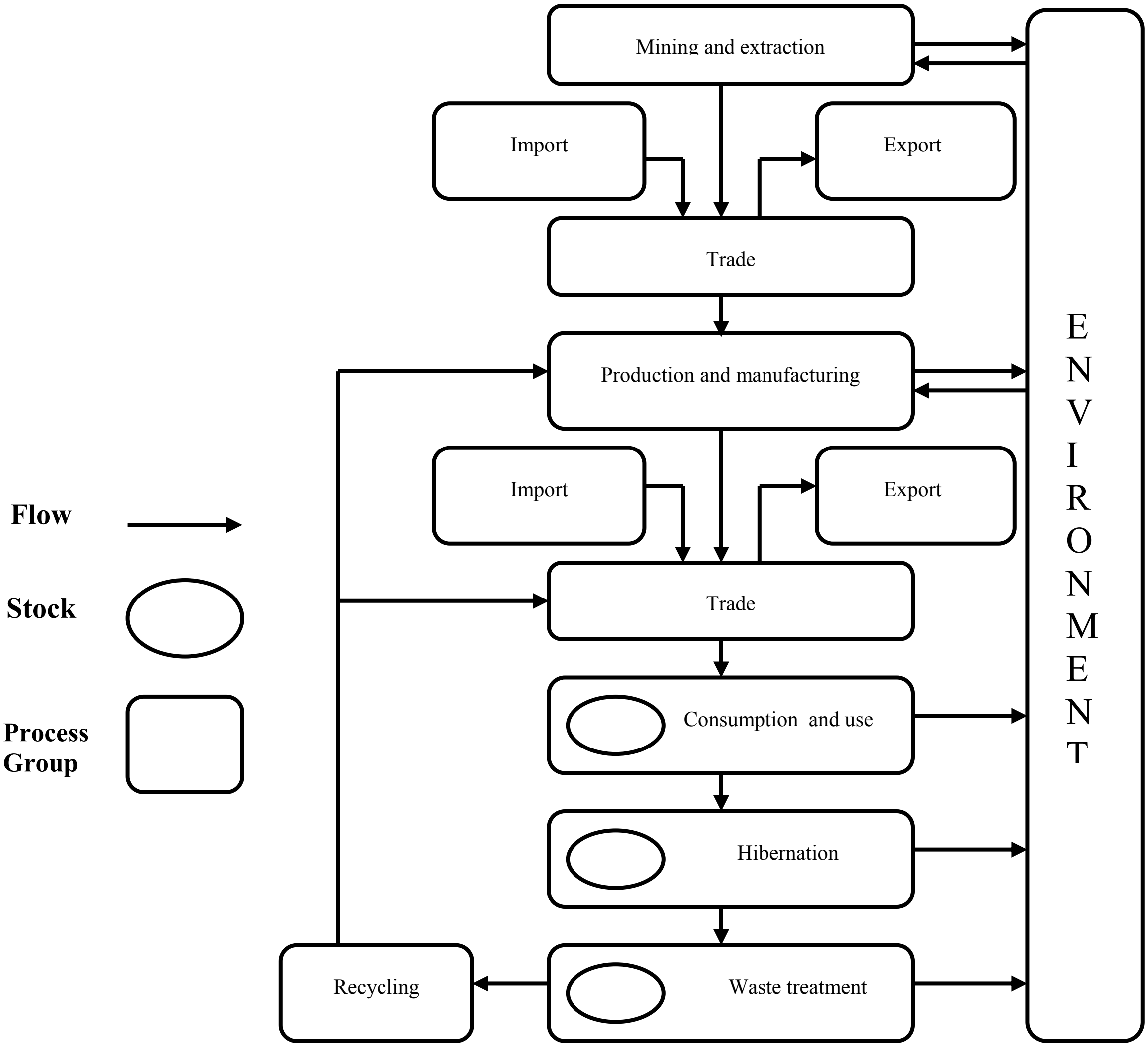


Figure 2.1: The main components of the economic subsystem

2.1 System components

As can be seen from figure 1, the main components of the system fall into three categories: flows, stocks and processes. The flows and stocks represent certain economic goods. Flows refer to goods travelling from one process to another. Stocks are goods stored within the economic system. In the processes, goods are transformed from one state to another. When this transformation takes place within one year, the goods will appear as flows in the SFA system. In case this transformation takes a longer time, the goods will appear as stocks.

2.1.1 Categories of processes

Mining and extraction, processes involving extraction of raw materials from the biosphere or geosphere and transformation of these raw materials into materials which can be used for production and manufacturing.

Production and manufacturing, processes involving the making of products, thereby transforming raw materials into finished goods.

Trade, processes transporting goods from one owner to another with no transformation of these goods.

Consumption and use, processes involving the consumption or use of products, thereby transforming them from products into discarded products. This process of use may involve a considerable time period.

Hibernation, processes involving storage of products no longer in use, but not yet discarded.

Waste treatment, processes involving the treatment of waste materials, thereby transforming discarded products into re-used products, recycled materials, landfilled waste, or emissions.

2.1.2 Categories of flows and stocks

Imported goods, **flow** of substances, materials, semi-manufactured goods and finished goods containing the substance–under-study into the system from outside the system. If we look at the economic subsystem, this flow represents trade with other countries (regions). Trade is induced by the economic mechanisms of supply and demand, and may be regulated by trade agreements. It is difficult to point out a primary actor – trade companies, producers and even consumers cause this flow.

Exported goods, **flow** of substances, materials, semi-manufactured goods and finished goods containing the substance–under-study out of the system. This flow represents trade as well.

Mined raw materials, flow of raw materials containing the substance–under-study extracted or mined from the domestic environment and entered into the economic system. The primary actor is the mining sector. The flow is influenced by the demand for these materials (manufacturers and consumers) and could be influenced by policy.

Products, **flow** of different kinds of finished goods containing the concerned substance into the consumption phase either production process inside the system or from outside the system by trade. Primary actor is the consumer. Policy makers, manufacturing and consumers influence the flow.

Products, **stock** of goods-in-use containing the substance–under-study providing the service they are made for. The stock is controlled by consumers.

Hibernating products, **stock** of goods containing the substance–under-study no longer providing the service they are made for. Some goods are no longer in use but not discarded yet. The stock is controlled by consumers.

Discarded products, **flow** of discarded goods from the consumption and/or hibernating phases to the waste processing phase. The flow is induced by consumers and handled by waste managers.

Reused products/recycled materials, **flow** of goods recaptured from the waste stream and returned to the consumption or production phase. The flow is controlled by waste managers and in some cases producers, and can be influenced by policy makers.

Landfilled waste, **stock** of final waste deposited at landfill sites. This stock is controlled by landfill site managers and can be influenced by policy makers.

Final waste, **flow** of valueless materials to be disposed of. At present the disposal is either landfill (see landfilled waste) or incineration. Ashes and slag from the incineration process may be recycled (see recycled materials) or end up in landfill (see landfilled waste). Materials may also be emitted to the environment (see emissions). The flow is controlled by waste managers and can be influenced by policy makers.

Emissions, flow of materials or substances from the economic to the environmental subsystem. Emissions represent losses from the processes in the economic subsystem through corrosion, leakage or volatilisation and can occur in all stages of the life cycle. The emissions themselves are out of control. However by making changes to certain processes, emissions may be reduced or prevented. The process owner controls this, but policy can influence it.

2.2 General classification of the stocks

SFA overviews typically cover a period of one year. Flows of goods appear within this year, goods are transferred from one process to another. In the use phase, goods with a life span of longer than 1 year tend to accumulate: they do not flow out again in the same year but remain in the use-process. Such applications with a life span of more than one year we refer to as stocks.

In SFA, a certain substance is always the object of investigation. All flows and stocks therefore are regarded only in terms of the substance and are specified in these terms. A substance may occur in a number of materials and in an even larger number of products. A substance stock therefore includes materials stocks, which in their turn include product stocks. The stock dynamics may result from developments on all three levels.

Stocks can be classified according to the following criteria:

- **Life span of the application**

The life span of the different stocks of applications of the substance under study can be different. For some applications, the life span could be very high (20 years or more) while for others, the life span could be a few years only.

- **Chemical form of the applications**

A Substance can be used as an element or as a compound.

- **Possibility for recycling**

Some of the substance applications are recycled in the sense that recycling scheme is established and operational. For some applications, recycling is technically possible but not established for example for economic reasons. For yet other applications, recycling is at present not possible.

- **Concentration**

In some products, the substance is present only in very low concentrations. These applications we call trace applications. In other products, the substance is one of the main elements. These we call bulk applications.

- **Intentionality of use**

In some applications, the substance is intentionally used because it provides a certain function in the product. In others, the substance is present only as a contaminant and fulfils no function.

- **Hibernation**

Most of the stocks in the economic subsystem will be in use. Hibernating stock refers to those applications, which no longer provide the service they made for but are not discarded yet.

- **Corrosiveness of the application**

Corrosion and slow leaching from the various substance applications and stocks may occur and end up in the soil or the sewage system. In some other applications this is not the case.

2.3 The main variables and parameters in the consumption and use phase

As can be seen in figure 1, the main stocks in the economic subsystem occur in the consumption-and-use phase. This refers to either stocks in use, or stocks in hibernation, which are not used anymore but technically, are still in the care of the user. When designing a model for stock dynamics, we therefore need to focus on the consumption-and-use (figure 2.2).

- The inflow into the stock in the consumption-and-use phase is, when using statistical data, a net inflow which can be calculated as the import plus the production minus the export of the goods in the economic subsystem.

- The outflow out of the stock is determined by the discarding one the one hand, and the emissions due to volatilization, corrosion or leakage on the other hand. When using statistical data, a net outflow can be calculated as the outflow due to delay plus the outflow due to leaching minus the recycling flow.

- The resulting stock (the accumulated goods in the consumption phase) then is equal to the accumulated inflow minus the accumulated outflow.

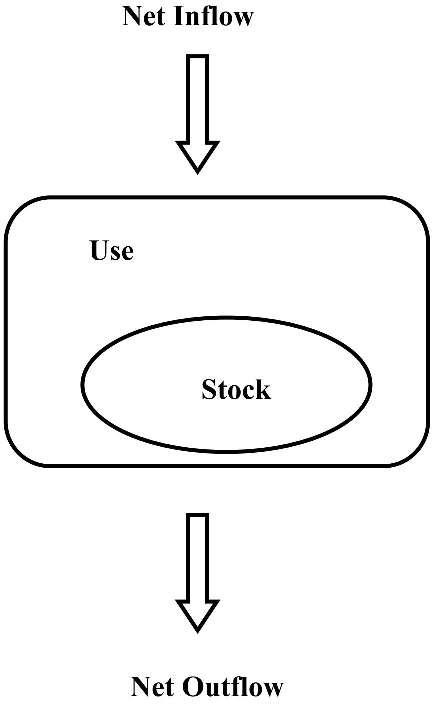


Figure 2.2: The consumption phase in the economic system

2.4 The main influential aspects

A careful distinction will have to be maintained between the stocks of products, handled by producers and consumers, the stocks of materials that those products are composed of, and the stocks of substances, contained within these products and materials and eventually resulting in emissions. Stocks of products, stocks of materials and stocks of substances have characteristic and different behaviour. In the design of a stock model we must account for this triple layer in the societal stocks.

A substance stock may contain several materials. Each of these materials is applied in a number of products. Products are associated with a demand; products have a life span, which may or may not be influenced by the substance it contains. The substance in a product may be substituted without changing the demand for the product. The substance in a waste material or the material in a waste product may be extracted and recycled, and consequently applied in different products. As a result, the substance leaves the specific product or material stock but not the economy, and the life span of the substance may differ considerably from the life span of each of its applications.

To develop a dynamic stock model, the inflow and outflow characteristics on the product level, material level and substance level should be considered in a dynamic sense. This could be done by using the historical data on the inflows and outflows of the system and establishing a relation between these flows and each of the influential aspects or by using external models, which describe the dynamic behaviour of these aspects.

The main influential aspects (product level)

On the level of the product we distinguish inflow and outflow characteristics (figure 2.3):

- Inflow characteristics determine how, through the years, the production of new products entering the stock develops. Examples of such mainly economic characteristics are: price of the product, correlation with income, sensitivity for trends, substitutability, etc.. Socio-economic aspects such as population size and GDP may also play a role, as well as technology developments.
- Outflow characteristics are related to emissions from the stock and the discarding of products. Corrosion of zinc from gutters or volatilization of CFCs from building materials are examples of emissions. Such emissions can be modelled as a fraction from the total stock by simple linear or exponential emission coefficients. Discarding of products rather can be viewed and modelled as a delay: the products entering the waste stage now are products that entered the stock some time back. The life span of the product and its distribution determine the shape of the discarding curve.

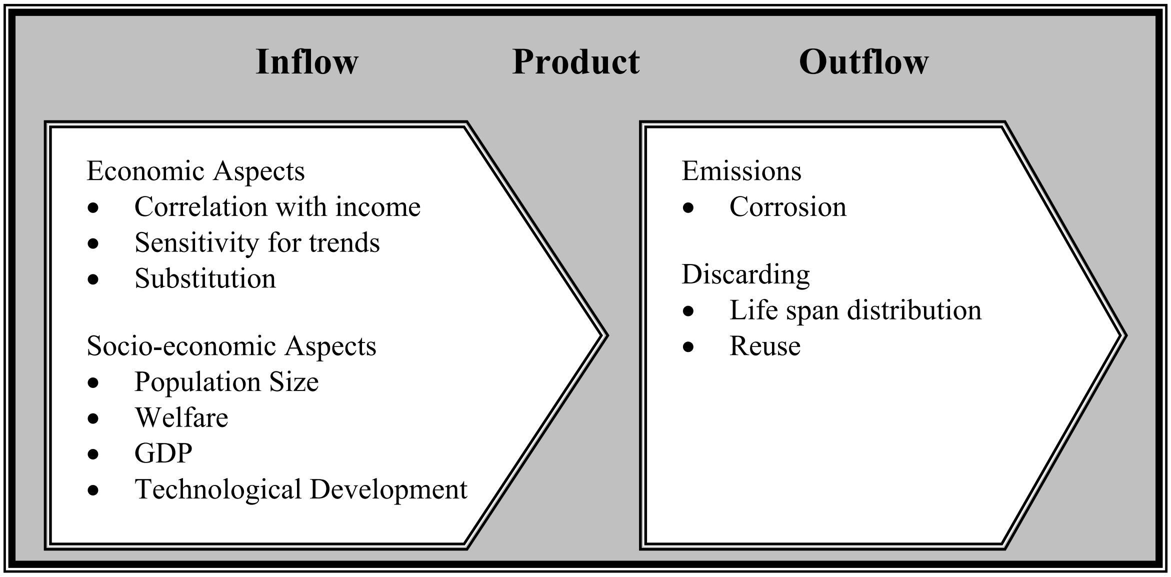


Figure 2.3: The inflow and the outflow characteristics on the level of the product

The main influential aspects (substance level)

On the level of the substance we define specific characteristics (figure 2.4):

- Inflow characteristics determine the intentional and unintentional occurrence of the substances in the product. Intentional characteristics: these are related to the function fulfilled by the substance in the product (for example: colour, mass, solidity etc.). Such characteristics determine the extent to which the substance may be substituted. In some cases the substance does not fulfil a function at all but occurs in the product as a contaminant. Such unintentional applications have their own difficulties, both in modelling and in management (Van der Voet et al., 1994; Guinée et al., 1998).

- Outflow characteristics (resource and materials characteristics): these are related to the chemical and physical properties of the substance and determine whether emissions from stock may take place (for example, volatility) or whether the substance may be extracted from the discarded products and recycled (for example, degradability).

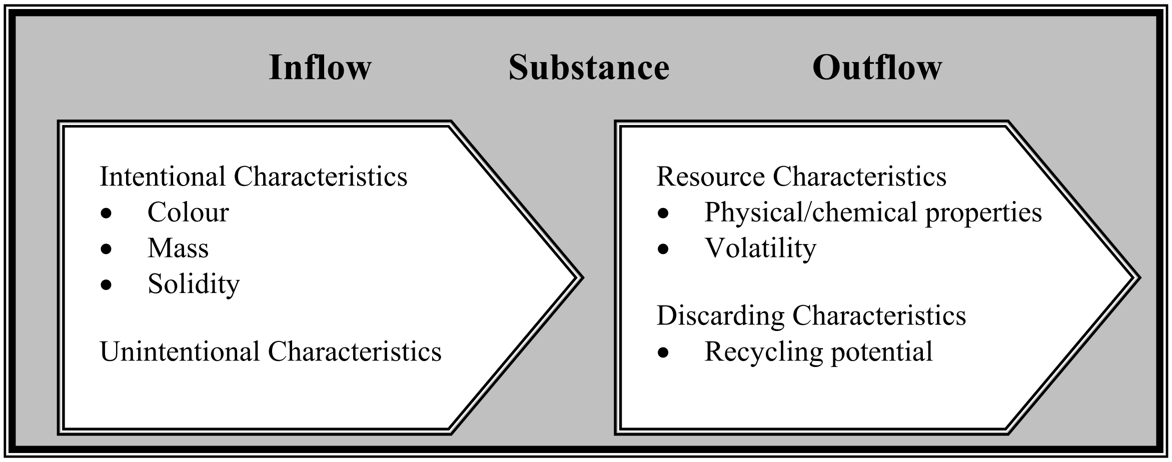


Figure 2.4: The inflow and the outflow characteristics on the level of the substance

The main influential aspects (material level)

As has been mentioned above, it is necessary sometimes to include the material as an intermediate level between the product and the substance levels. This is mainly due to the fact that sometimes the main target is the recycling of materials. Sometimes, the substance may exist as a contaminant in the recycled material (i.e. glass recycling). Moreover, there could be substitution between materials and as a result the substance inflow will be affected indirectly.

The main influential aspects on the material level could be distinguished as inflow and outflow characteristics. The inflow is mainly characterised by economic factors such as the material price and material substitution. The outflow is mainly determined by the material's physical and chemical properties which ultimately determine the possibility of recycling and the emissions from the material stock during use.

2.4.1 The main influential aspects (inflow level)

2.4.1.1 Substitution

Substitution is defined as the replacement of one material by another material or replacing one product by another product without changing the function or use of the material or product (Kandelaars, 1998). The viability of a substitute can be based on, whether the substitute can function adequately as a replacement, whether the manufacture and disposal of a substitute reduce environmental consequences, whether the cost/environmental benefit of the substitute is sufficiently attractive, and other factors such as governmental action to promote the substitute.

Substitution can be defined at all three levels: product substitution, material substitution and substance substitution.

Product substitution

Substitution of one product by another product may be affected by three actors, consumers, producers and policy makers. The substitution could take place due to environmental, economic or technological factors, or a mix of any of these (figure 2.5). Environmental factors include the concern about the emissions or the possibilities of product reuse. Economic factors can be linked to the consumers and producers. Consumers may replace the product by another providing the same service for reasons such as, lower price, a more fashionable image or a lower cost of using the product. Producers may replace product by another because of the price they have to pay or the inputs, the price they can ask for the product, or the cost of the production process. Technological factors may affect the substitution of a product via a new design for products or production techniques.

Material substitution

Consumers play no direct role in material substitution, but may indirectly influence this by showing a preference on the consumer market. Material substitution may take place for a number of reasons, which also can be classified as environmental, economic and technological. Environmental reasons refer to the preference for another material for environmental reasons, F.E. causing less emissions, containing less hazardous substances, leading to less landscape degradation or involving less health risks. Economic reasons can be found in the price of the alternative material. Technological reasons refer to for example the composition of a new material or new ways to process existing materials.

Substance substitution

For substance substitution, the same reasoning holds: consumers do not influence this directly, but may have a significant indirect influence through demand. Environmental reasons are even more direct and can be related to risk assessment or substance oriented policies. An alternative must be found to do the same job, for example giving a material its colour or flexibility. This is not always possible. Sometimes it leads to a material substitution as well. A specific category is the non-intentional applications: these do not fulfil any function and could be left out from that point of view, but they occur in the material as a contaminant and must be intentionally extracted. This is not always possible and often expensive, but has been known to happen as a result of strict environmental policies.

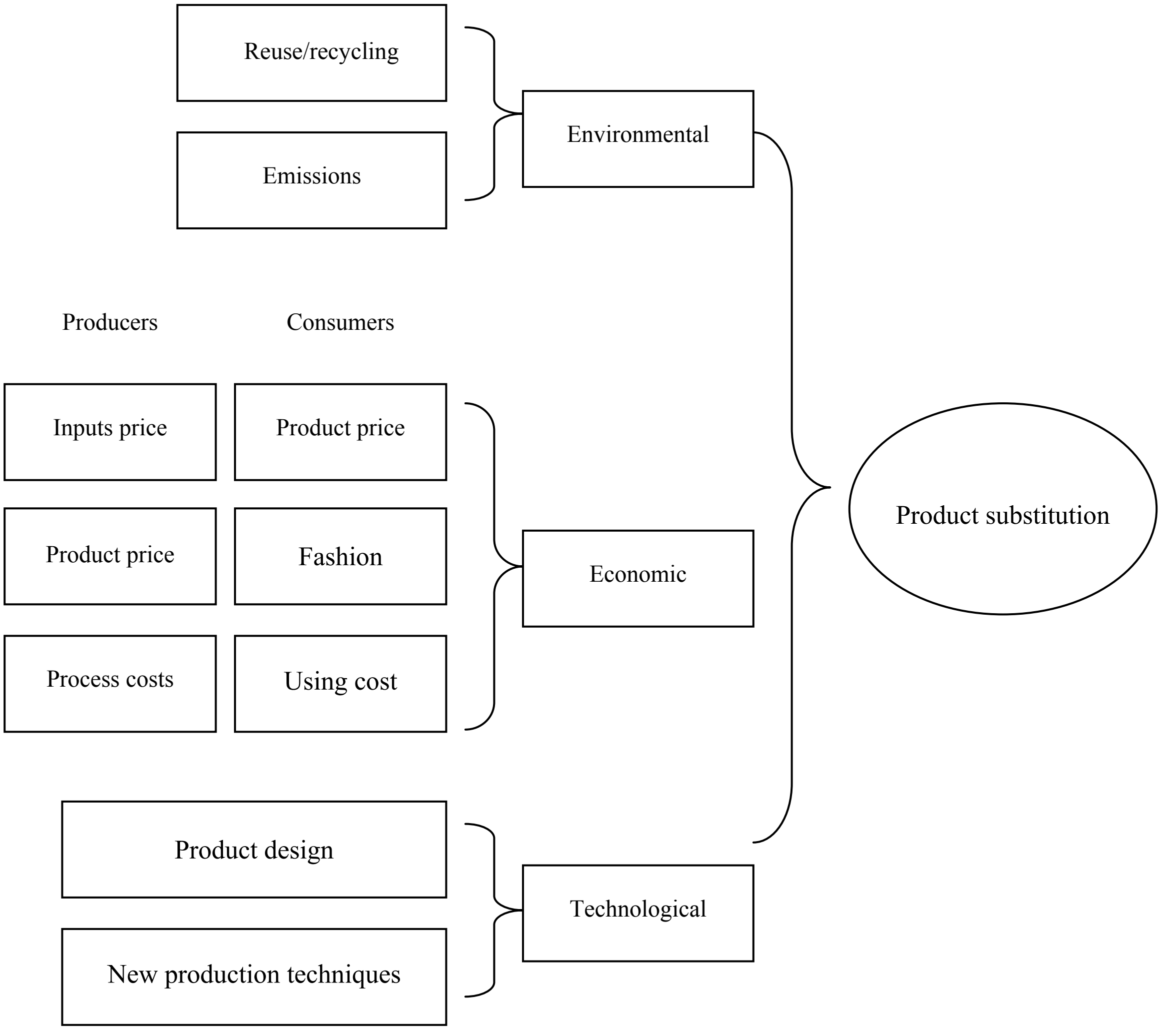


Figure 2.5: The main factors determining product substitution

2.4.1.2 Correlation with income

Some products will be bought regardless of the specific income situation of consumers, such as food, clothing, and furniture. These “basic needs” may change over time, when the general welfare situation of a nation increases. In Western Europe, people consider a washing machine, a computer or even a car a basic need, which 50 years ago was not the case. Such changes are gradual.

Other products will be more subject to differentiation depending on the income. Sometimes it will be variations on the basic needs, such as very expensive foodstuffs, designer clothes and suchlike. For some goods a correlation with the income may show. The income distribution then may be a relevant parameter to describe the inflow of such goods.

2.4.1.3 Sensitivity for trends

Some products are very trend sensitive. Specific games or toys, like tamagotchis, furbies, Pokémon cards suddenly appear in great masses and are completely forgotten a few years later. Computer games also become outdated quite soon and a newer version is required in order to maintain standing among friends. In the adult world, these toys are laptop computers, digital cameras, the latest mobile phones or far-away holidays. For such trend sensitive products, it will be difficult to establish any correlation whatsoever, which implies that it will be quite impossible to make any predictions of a future inflow. In a dynamic model, external assumptions will have to be made for these products.

2.4.1.4 Gross Domestic Product

Gross Domestic Product (GDP) or Per capita GDP is a standard measure of basic economic growth. Poverty, natural resources exploitation, consumption and production are all intimately connected to it, either positively or negatively. Many studies are devoted to describing the relationship between GDP and a number of environmentally relevant variables, such as certain emissions esp. SO2 and CO2, and the use of materials on a general level. Although it was concluded that in some cases for some countries, there seems to be a recent de-linking of GDP and these variables, still it is understood that the economic growth is related to a growth in the physical economy as well. On a general level, the correlation between GDP and materials use still is valid. It may be that for specific substances, materials or products this correlation also can be used. For example Tiltone has established such a relation for the intensity of metals use in general for the US (Tiltone, 1996).

GDP reflects changes in total production of goods and services. The levels of GDP per capita are obtained by dividing annual or period GDP at current market prices by population.

GDP as described in 1993 system of national account (SNA) can be defined in three ways: firstly, it is the sum total value added of all production units including all taxes and subsidies on products which are not included in the valuation of the output. It is also equal to the sum of final uses of goods and services (except intermediate consumption) measured in purchasers prices, less the value of imports of goods and services. Finally, it can be measured as the sum of primary income distributed by resident producer units.

Five factors normally contribute to the economic growth (figure 2.6)
- Labour input, which reflects the contribution of changes in (a) man hours worked (b) labour quality (c) underemployment or labour hoarding;
- Capital input, which indicates the percentage of GDP growth caused by change in (a) the quantity of capital (b) the quality of capital (c) the abnormal slack in the use of physical capital;
- The catch-up effect, which capture the benefits that countries other than the USA enjoy from their relative technological backwardness;
- Structural shift, which measure the contribution of the movement of employment from agriculture to industry and more recently from both agriculture and industry to service;
- Other consideration which include (a) the beneficial effects of the growth in foreign trade and economic scale (b) the simulating effects of north sea oil and gas development for the British economy (c) the adverse consequences of crime and governmental regulation as well as higher energy price during the 1970's.

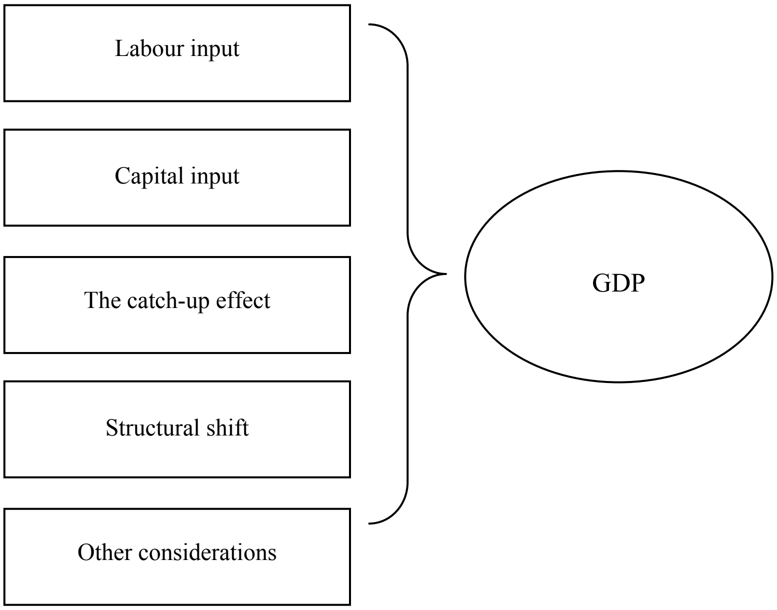


Figure 2.6: The main factors contribute to the economic growth

GDP can be broken down into different parts. When finding explanatory factors for products and especially materials inflow, it may be more relevant to look at the share in the GDP by the relevant sector (intersectoral shift) and the share in the individual sectors (intrasectoral shift) (Tiltone, 1990).

Intersectoral shift refers to the shift within the economic sector. For example, the shift from agricultural to manufacturing in the past and more recently from both the agricultural and manufacturing to service.

Intrasectoral shift refers to the shift within the individual sector in particular within the manufacturing sector. For example, computers and other high tech goods account for a much larger share in the manufacturing sector today than in the past, the opposite is true for motor vehicles. The intrasectoral shift determines mainly the consumers need and preferences.

GDP growth

The projected average GDP growth for the EU is expected to be 2.4% per year from 2001 to 2010 and 1.8% per year from 2011 to 2020 according to the Baseline Scenario. These figures have been changed in different scenarios such as the Technology Driven Scenario and Accelerated Policy Scenario since the changes in these scenarios induce a loss in GDP at the national level and the EU level (RIVM, 2001). The percentage of GDP growth based on different scenarios from 2000 to 2030 can be found in the appendix.

2.4.1.5 Other measures of welfare

Welfare or well being of a society is one of the determinant factors of the dynamic behaviour of the inflow curve. Several factors should be considered in the welfare indicators (Stockhammer et al, 1997). These are (1) Non-market production (2) Various parts of production that are not disposable for consumption but are needed to repair damages caused by the economic system itself (3) Environmental damages that are not repaired (4) The reduction of future welfare caused by production/consumption today (5) The effort required to obtain this welfare (6) The income distribution.

In the past, GDP has often been put on a par with increasing welfare or well being of the society. In fact, GDP is not intended to be a measure of societal welfare, but it is often used as such. GDP is considered by many to be a lame measure welfare (Turner, 1999). The limitation of GDP is that it does not account for the social and environmental costs of production; it therefore is not a good measure of the level of over all well being. Moreover, it does not allow for the natural capital used up in the production process. Overexploitation of natural resources as well as damage by pollution is not included in the GDP indicator.

More specific reasons why GDP is not a good measure of welfare are:

- GDP treats crime, divorce and natural disasters as economic gain;
- GDP ignores the non-market economy of household and community;
- GDP treats the depletion of natural capital as income;
- GDP increases with polluting activities and then again with clean ups;
- GDP takes no account for income distribution;
- GDP ignores the drawbacks of living on foreign assets.

There are alternatives for GDP as a measure of welfare such as the Genuine Progress Indicator (GPI) and the Index of Sustainable Economic Welfare (ISEW).

ISEW is one of the most advanced attempts to create an indicator of economic welfare, it is combining social factors, income inequality and environmental deterioration (all components that have an evident impact on peoples quality of life). Overexploitation of natural resources clearly has negative consequences for the development of welfare, which is expressed in the ISEW. It can be imagined therefore that ISEW may correlate better with the development of materials use in general than GDP. However, ISEW has not been calculated for all countries (e.g. Belgium) and recent data are missing for almost all countries.

2.4.1.6 Population

There are several reasons to consider population an influential variable for determining the use of materials in general and some materials in particular. In the first place, there is the general law that it takes more to sustain more people. This refers mainly to the basic needs: for example the demand for food in terms of nutrients will be linked to the number of people more than to anything else. In the second place, the changes in size and composition of the population may be an indicator for some environmental variables in general, and the use of materials in particular.

Population provides an important contextual reference on sustainable development when the interrelation between people, resources, the environment and development is regarded. Population change is a significant signal determining poverty, the level of economic progress, environmental protection, and consumption and production levels.

Fertility rates and population growth rates are declining in most countries, especially in the industrialised regions of the world. Nevertheless, the absolute population number is still increasing in all regions of the world.

The population growth rate

The population growth rate measures how fast the size of the population is changing. As an indicator it is related to human settlements and the use of natural resources, including sink capacities (UN). The rate of population growth, r, between two times, t_1 and t_2, is calculated as an exponential rate of growth, conventionally expressed in units of percent per year.

$$R = 100 \ln (P_2/P_1)/(t_2-t_1)$$

P_1 and P_2 are the number of people at time 1 and 2, respectively and the time interval (t_2-t_1) is expressed in years.

The population of the EU is expected to increase slightly during the first decade of the next millennium (2000 – 2010) primarily due to immigration. After 2010, the rate of population growth falls and is expected to stabilized after 2020. EU population is projected to be more than 386 million people by 2010 based on the baseline scenario (RIVM, 2001). An exact percentage of the population growth from 1995 to 2010 can be found in the appendix.

2.4.1.7 Technological developments

Technological developments generally are discrete events that occur at irregular intervals. The occurrence of such developments, the speed of adoption and the ultimate impact on the use of materials in a specific application all vary greatly in response to a variety of factors, including the opportunities they provide to reduce costs and expanding markets. (Tilton, 1990). Technological development to a certain extent is connected with material and product substitution, since it can facilitate the substitution and recycling. It can also lead to change in product design or process efficiency, thereby enabling to reduce the quantity of material used for the product.

Technological change as classified by Kemp (1997) can be fit into three categories (figure 2.7):

- production process changes such as end of pipe technology and process integrated technology;
- product changes such as product reformation and product substitution;
- new technology systems.

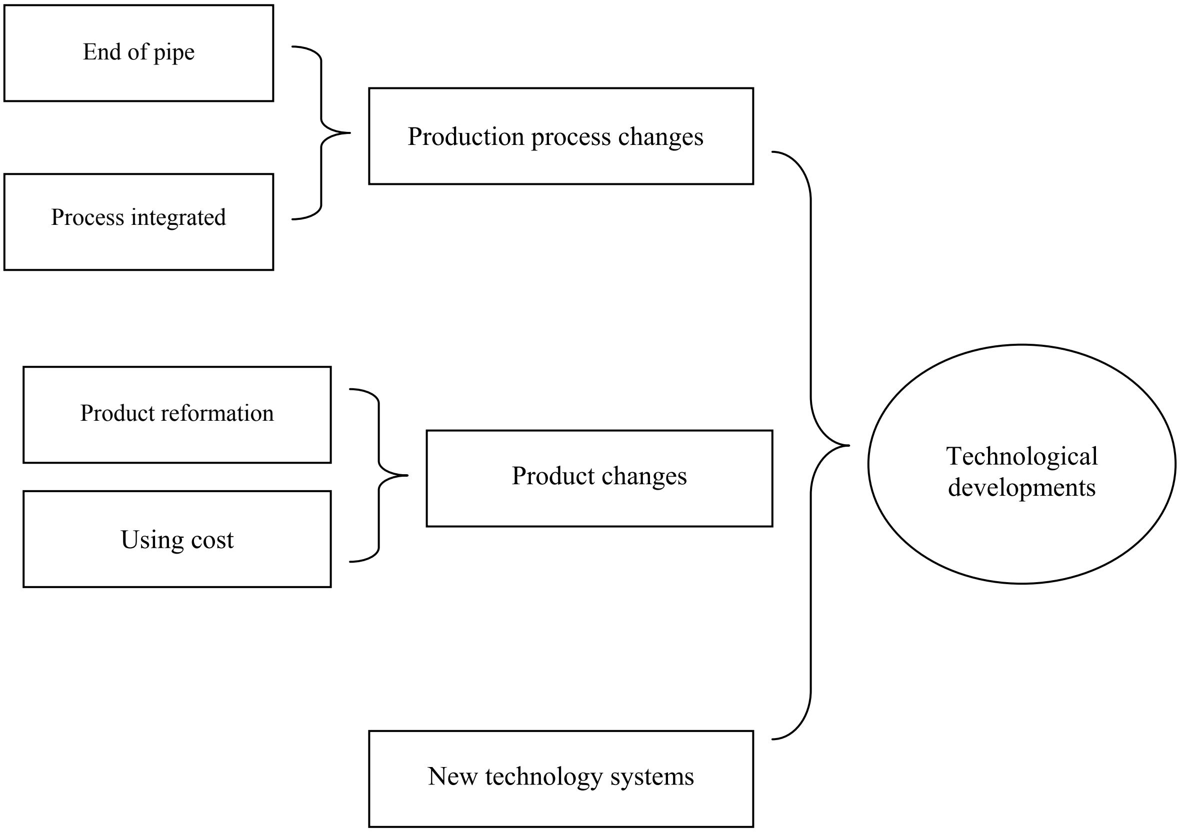


Figure 2.7: Classification of possible technological changes

2.4.2 The main influential aspects (outflow level)

The influential aspects for the inflow of products into a stock are much more divers and complicated than for the outflow. On the product level, the outflow is completely determined by the inflow combined with the life span of the product. On the material level, recycling may complicate the issue a bit. On the substance level, there are the emissions during use due to corrosion or volatilisation, which are determined by the physical and chemical properties of the substance.

2.4.2.1 Life span distribution

The outflow or the discarding of a certain product from the consumption phase depends mainly on the product life span. To obtain an accurate picture of stock formation and depletion the distribution of the life span should be known (Kleijn et al., 2000). The empirical data on the life span is often not available. An alternative is to assume either an average life span or a certain life span distribution. Possible types of distribution are normal distribution, and skewed distribution. When the points are expected to be more concentrated in the middle than in the tails, normal distribution gives a good result. When one of the distribution tails is longer than the other, assuming skewed distribution will be more accurate. The normal distribution is defined by two parameters, the mean (μ) and the standard deviation (σ) and has a skew of 0 since it is a symmetric distribution.

2.4.2.2 Reuse and recycling

Recycling of materials and reusing of product is a way to minimize the extraction flow and the amount of waste to be incinerated and/or landfilled, however, recycling 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 recycling centre.

The determinant factors of recycling are technical (is recycling technically possible or not?), economic (is recycling economically feasible or not?) and environmental (sometimes governments may impose policies to simulate recycling for environmental protection reasons) (figure 2.8).

The collection rate of the applications is an important factor for recycling. For example the collection rate of batteries is high in most of Western Europe and the recycling potential of batteries is very high. More recently, an EU Batteries Directive obliges Member States to ensure a high rate of battery collection. Different countries have approached this in various ways. Stated collection targets range from 100% in France, and 99.9% in Denmark, to 75% in Portugal. This is will effect the recycling potential in the future.

An important factor for collection is the economic value. For example cables are sometimes recovered after use for the recycling of copper. However, it is often not economic to collect old cables, as collection can be more expensive than the value of the metals. Another important factor for collection is public awareness and cooperation

2.4.2.3 Emissions during use

Some applications lead to emissions due to corrosion and slow leaching of substances from various stocks of applications. These emissions may end up in the soil, water or sewage system. Corrosion of materials from certain applications sometimes occurs due to the fact that they are exposed to the atmosphere and rainwater. Generally the corrosion will increase in acid environments, which is the case in the humus layer of the soil or as a result of acid rain.

In order to estimate the yearly emissions during use of a certain application, the size of the stock should be estimated. Such emissions can be modelled as a fraction from the total stock by simple linear or exponential emission coefficients.

In the landfill sites, the leakage depends on many parameters, like the stock of materials (composition and amount) present at the site, the weather and hydrological conditions and the way the site is controlled (covered or not covered, treatment of waste water from the site et cetera.). For most material inflows to landfill, the fraction of the material in landfill that might be mobilized should be taken into account when a corrosion factor is to be calculated.

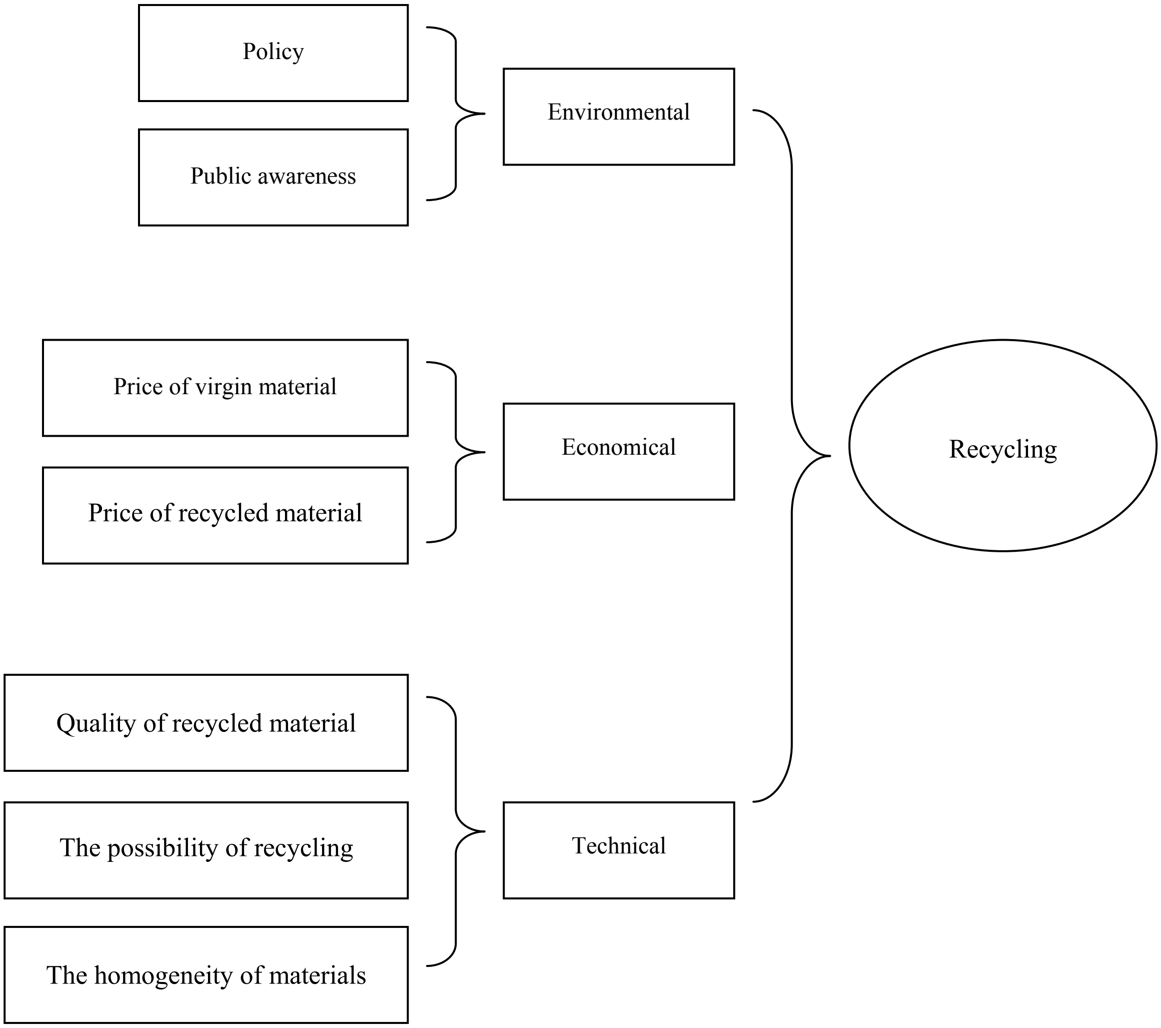


Figure 2.8: The determinant factors of recycling

3 THE APPROACH IN THE ANALYSIS

3.1 Product stocks

3.1.1 Modelling the stock's inflow

In the previous sections, several factors determining the shape of the inflow curve over time have been discussed. These factors are GDP, the sectoral share in GDP, population, welfare as described by the ISEW indicator, technological developments, substitution and income distribution. In this section, the subject is how to translate these factors into modelling parameters for a dynamic stock model, which can be used to make a meaningful estimate of the future inflow into the stock.

When conducting a case study, the first step is to make a qualitative assessment. It needs to be established, for example, whether or not there are any substitutes for the product, and if so what their specifications are regarding material composition, performance of service, and price. It needs to be established whether or not the product at present is subject to rapid change due to technological improvements, and if so, in which direction. It needs to be established whether the product in question is sensitive to fashion. This will provide a first insight in the factors that are relevant for determining the future inflow curve. The second step is then to determine the relative importance of the various parameters. To assess which of these factors will contribute mostly to the shape of the inflow curve, we divided them in five groups as shown in figure 3.1.

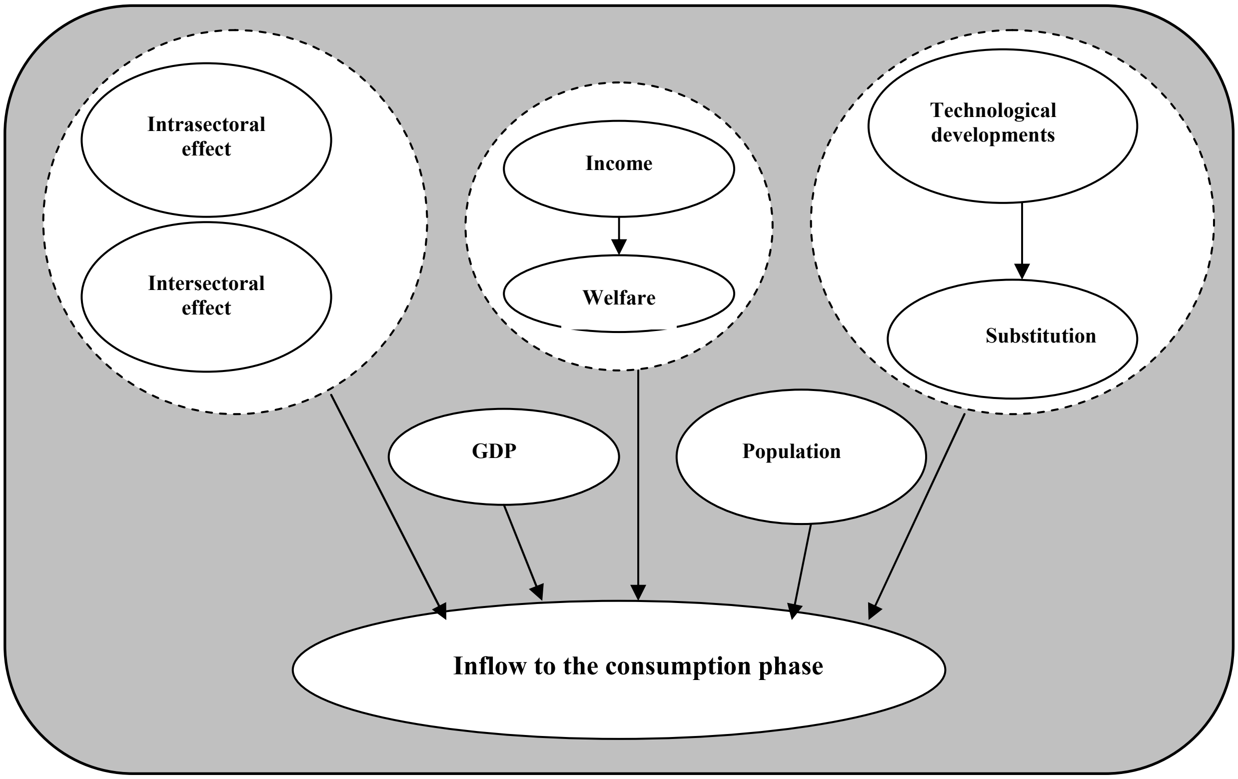


Figure 3.1: The five groups of factors determining the shape of the inflow curve over time

The procedure is as follows:

1- Establish correlation between the inflow curve and the parameters

The first step is to examine, whether a correlation exists between the inflow curve and some of these parameters. This is done by correlating the inflow curve for the past with the developments of the influential aspects in the past using regression analysis (equation 1). The goodness of the correlation can be evaluated on the basis of the coefficient of determination (R^2) to indicate the overall tightness of the correlation, and of T-statistics to indicate the significance of the variable. Moreover, the sign associated with the variable's coefficient is an important indicator. For example, the inflow is expected to correlate negatively with the price, however, sometimes the numerical results show a positive correlation between the inflow and the price. This means, even if R^2 is high and the variable is significant, the correlation can not be used. The aspects which may correlate with the past inflow are GDP, intersectoral (manufacturing, services), intrasectoral (high tech goods), population size and growth, welfare, income distribution. For technological development and substitution, no general indicator exists which can be correlated. The assumption is that if the correlation with the mentioned parameters is low, the inflow curve may be determined mainly by substitution and/or technological development. For welfare, sometimes it is not possible to use the welfare indicator ISEW due to the fact that this indicator is calculated for a limited number of countries (for example, it is not calculated for Belgium) and only for a few years (time series covering the whole study period are not available). In this case GDP could be used as indicator to capture the affect of the nation welfare.

Sometimes the inflow in a certain year is not corresponding to the change in the socio-economic variables in the same year, but it might correspond with socio-economic developments of some number of years in the past. In a mathematical form, this time lag could be accounted for as given by equation 2.

2- Establish the relative importance of the parameters

The second step is measuring the importance of those influential variables, which are correlated with the inflow curve. This can be done by using different statistical terms. The adjusted coefficient of determination (R^2adj) and F-statistics can be used to determine the overall goodness of the correlation when adding a new variable to the regression model. T-statistics can be used to evaluate the significance of the individual variables in the model. On the basis of these statistical terms, the best model fit the data can be chosen. R^2 is a measure of how much of the variance in the dependent variable is explained by the independent variables in the regression model. Large values of R^2 indicate better agreement between the model and the data, however, R^2 will always increase as more variables are added to the model. Alternatively, R^2adj can be used when more than one variable are combined in the model because it takes into account the number of independent variables. F-statistics indicate whether adding another potential variable to the regression model significantly improves the quality of the fit. T-statistics indicate whether or not each regression coefficient is significantly different from zero. For F-statistics and t-statistics, the critical value which is indicating the significance of the model or its individual variables at different probability levels can be found in any statistical book.

3- Establish the relation between the important influential aspects and the inflow curve

The third step is to determine the relation between the important parameters and the inflow curve. This is a relation in a mathematical sense, describing how the inflow exactly depends on the parameters. If technological development or substitution is important, we have to look behind those to see what exactly in this case is important. In the case of substitution, it could be the price of the alternative relative to the price of the original product. In the case of technological development, it could be the presence of specific new technologies relevant for the product.

4- Predicting the future trend of the inflow

The fourth and final step is then to estimate the future trend of the inflow curve. This is could be done by using the established equation directly with projections of the parameters in this equation. In some cases, it could be more accurate to look behind these variables, or in other words at what makes these variables evolve over time. If no good mathematical relation can be established from the parameters at all, we will have to fall back to other means. A possibility is to use the past inflow trend and just extrapolate it to the future. Another possibility is to make own assumptions about the future inflow, for example based on expert opinion or intended policies. The inflow curve could then be described in general form as given by equation 1.

$$\mathit{Inflow}\ (t) = \beta_0 + \beta_1 X_1\ (t) + \beta_2 X_2\ (t) + \beta_3 X_3\ (t) + \beta_4 X_4\ (t) + \beta_5 X_5\ (t) + \varepsilon\ (t) \tag{1}$$

Inflow (t) is the inflow to the stock of products-in-use at time t
$X_1(t)$ - $X_5(t)$are the socio-economic variables at time t
β_0, is the intercept, β_1, β_2, β_3, β_4, β_5 are the corresponding coefficients, and ε is an error term

$$\mathit{inflow}\ (t) = \beta_0 + \beta_1 X_1(t-i) + \beta_2 X_2(t-i) + \beta_3 X_3(t-i) + \beta_4 X_4(t-i) + \beta_5 X_5\ (t) + \varepsilon\ (t) \tag{2}$$

X(t-i) is the socio-economic variables at time (t-i), i = 0,1,2………..

3.1.2 Modelling the stock's outflow

As stated before, the outflow out of the stocks depend on the mechanisms of delay and leaching. Delay is determined by the life span of the products: the outflow is determined by the past inflow, delayed by the life span of the application. The life span of the material or substance may be different from that of the products due to recycling. Leaching refers to the emissions of the substance during the process of use of the products containing the substance. The trend in the outflow curve therefore will be determined by three basic determinants (figure 3.2): the emissions during use, the amount of reuse and recycling, and the life span. These three parameters are at work independently from each other and can be modelled separately.

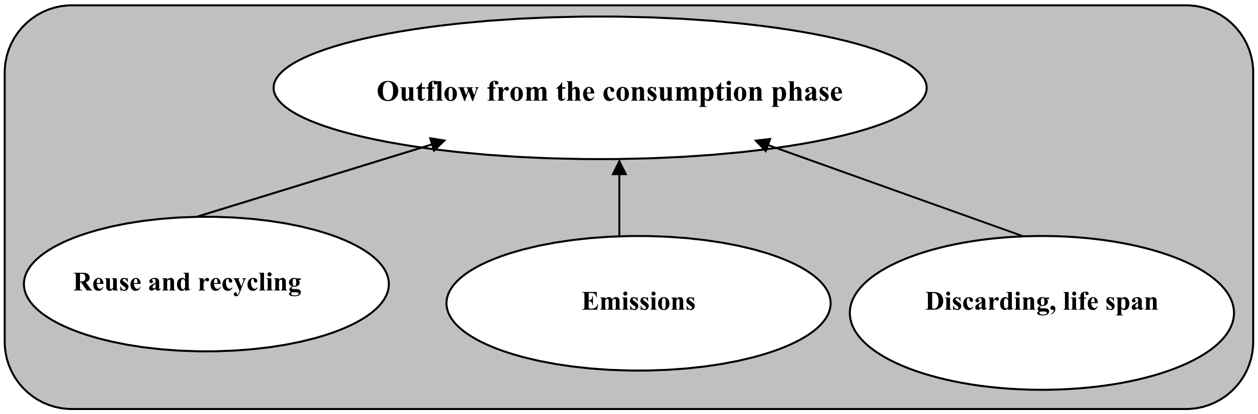


Figure 3.2: The three basic determinants of the outflow curve

Life span

The life span of the applications containing the substance can be established as an average life span. It is also possible and probably more accurate to establish a life span distribution, as discussed in Section 2. Data on life span are available in many cases. If not, an estimate must be made based on expert judgement.
The outflow of the product stock due to discarding will be translated into model equation. This equation will have the following shape:

$$O(t) = I(t - L) \qquad (3)$$

with O(t) the outflow at time t, I the inflow and L the life span.

Emissions during use

The emissions during use can be described as a fraction of the stock. For different applications, an emission rate can be established. For heavy metals for example, there are studies aimed at establishing a corrosion coefficient. If it is not possible to take such coefficients from the literature, an estimate based on expert judgement must be made.

Emissions during use are calculated as a fraction of the stock-in-use:

$$O(t) = c * S(t) \qquad (4)$$

with S the size of the stock and c as a constant leaching factor.

Reuse and recycling

Reuse of products will delay the outflow out of the product stock by lengthening the life span. In most cases, a reuse percentage will be known. If not, a choice must be made to either ignore reuse (in case of a very low reuse rate) or make an estimate based on expert judgement. In the case of recycling of materials, the outflow out of the product stock will not be affected. However the outflow out of the material stock is affected. The material system will therefore include more processes than the product stock, which is defined as a stock in the consumption phase. Substance recycling may include even more processes, since different materials containing the substance may be recycled, and moreover the substance may be extracted from the material and be re-entered into the production phase. For materials and substances as well, recycling rates will be available in many cases. If not, they may have to be composed out of the recycling rates of the underlying levels. As mentioned before, a recycling rate is composed out of two elements: the collection percentage, and the recovered fraction in the recycling process.
Reuse and recycling can be modelled as a fraction of the outflow by discarding, per application. The equation will be in the following shape:

$$R(t) = \alpha * O(t) \qquad (5)$$

with R the amount of reused products or recycled materials, α the recycling rate and O the outflow out of the product stock.

In general term, the outflow from the consumption–and–use phase will be calculated by the following equation

$$O(t) = O(t)delay + O(t)\ leaching - R(t) \qquad (6)$$

3.2 Substance stocks

The dynamic behaviour of the stock in the consumption – and – use phase is determined by dynamics on three levels: the product stocks dynamic, material stock dynamic, and the dynamics of substance stocks. The dynamics of a certain substance stock is determined by its inflow and outflow characteristics. The inflow characteristics are determining how through the years, the inflow of substance evolves as a result of the function that the substance fulfils in particular application. Sometimes the substance may occur as a contaminant, in this case, the dynamic behaviour is determined in different way. The outflow of substance is mainly controlled by its chemical and physical properties as well as by the possibilities of recycling.

3.2.1 Modelling the substance stock's inflow

The inflow of substances to the consumption – and – use phase is determined mainly by the function fulfilled by the substances in particular goods. The use of substances due to their functions are affected by several factors. Among these is the availability of substitutes that can perform the same function. Environmental policy or other developments may force such substitution, or advance the use of a certain substance due to its recyclability. 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.

Two approaches can be used to model the inflow of substances to the stock of products-in-use. The first approach is to estimate the inflow into the substance stock as the sum of all product inflows, which can be modelled as a function of the socio-economic variables, multiplied by the fraction of the weight that is taken up by the substance as given by equation 7.

$$F^{in} sub(t) = \sum_{i=1}^{n} F^{in} prod(i) * \alpha(i) \tag{7}$$

where F^{in}sub is the total inflow of the substance, F^{in}prod is the inflow of different products and α is the substance composition of each product.

This approach is used in the estimation of the substance inflow in this study.

A second approach is to estimate the inflow into the substance stock on basis of the substance's economic characteristics, that is, the function fulfilled by the substance in the products. These economic characteristics strongly depend on the physical and chemical properties of the substance. This approach can be done by the following steps:

- A qualitative analysis – analysing the main function of the substance in its different applications;
- A quantitative analysis – quantifying the amount of the substance entering the stocks of different applications in the same function;
- Explaining the shape and the trend of the inflow curves for these groups based on knowledge of the past in a similar manner to the inflow on the product level, i.e. by finding explanatory variables;
- Compare the quantity of the substance in these application groups with the total amount consumed by all applications (inflow of the substance) and possibly calculate the relation between these groups and the total consumption;
- Estimation of the possible future trend based on the trend in the past and information on the current and expected future situation.

This approach is just an idea to be investigated in the future, however, in this study the first two steps will be implemented for lead in the EU as an example.

3.2.1.1 Qualitative analysis of the main lead applications and main functions

Lead has unique properties, which make it useful in many applications. These are its density, malleability, lubricity, flexibility, electrical conductivity, and coefficient of thermal expansion, all of which are high. Its elastic modulus, elastic limit, strength, hardness, and melting point, all of which are low. Lead has also a good corrosion resistance in many conditions. The high density of lead makes it very effective as a radiation shielding substance. The high density of lead in combination with high limpness (low stiffness) and high damping capacity makes it an effective sound proofing substance, its high corrosion resistance makes it effective in the manufacturing of batteries, paint and many other applications. Table 3.1 shows the consumption of lead by different application in the period 1993 - 1998. Tables 3.2, 3.3, 3.4, 3.5 and 3.6 show the main lead applications and the function fulfilled by the lead in these applications.

Table 3.1: The EU consumption of lead from 1993-1998, (ktonnes of Pb)

Application	1993	1994	1995	1996	1997	1998
Batteries	**743**	**822**	**869**	**870**	**888**	**919**
SLI batteries	579.54	641.16	677.82	678.6	692.64	716.82
Motive power	104.02	115.08	121.66	121.8	124.32	128.66
Industrial	59.44	65.76	69.52	69.6	71.04	73.52
Consumer	7.43	8.22	8.69	8.7	8.88	9.19
Rolled & extruded	**214**	**218**	**234**	**221**	**222**	**233**
Building materials (lead sheets)	171.2	174.4	187.2	176.8	177.6	186.4
Pipes	0	0	0	0	0	0
Radiation shielding materials	21.4	21.8	23.4	22.1	22.2	23.3
Sound proofing materials	6.42	6.56	7.02	6.63	6.66	6.99
Chemical applications	10.7	10.9	11.7	11.05	11.1	11.65
Collapsible tubes	0	0	0	0	0	0
Wine bottle capsules	4.28	4.36	4.68	4.42	4.44	4.66
Pigments & other compound	**203**	**206**	**211**	**196**	**201**	**193**
Glass pigments - Cathode ray tube	81.403	82.606	84.611	78.596	80.601	77.393
Glass pigments – Crystal	31.262	31.724	32.494	30.184	30.954	29.722
Glass pigments - Optical glass	7.511	7.622	7.807	7.252	7.437	7.141
Glass pigments - Light bulbs	4.872	4.944	5.064	4.704	4.824	4.632
Other – Plastic additives	46.487	47.174	48.319	44.884	46.029	44.197
Other – Glazes	18.676	18.952	19.412	18.032	18.492	17.756
Other – Paints	9.338	9.476	9.706	9.016	9.246	8.878
Other – Ceramics	3.045	3.09	3.165	2.94	3.015	2.895
Shot and ammunition	**53**	**52**	**55**	**56**	**57**	**59**
Sporting shot	42.93	42.12	44.55	45.36	46.17	47.79
Steelmalding shot	10.07	9.88	10.45	10.64	10.83	11.21
Alloys	**37**	**40**	**40**	**36**	**33**	**32**
Solder – electronics	14.8	16	16	14.4	13.2	12.8
Solder – plumbing	3.7629	4.068	4.068	3.6612	3.3561	3.2544
Solder – car radiators	2.7602	2.984	2.984	2.6856	2.4618	2.3872
Solder- car body	2.5086	2.712	2.712	2.4408	2.2374	2.1696
Solder – food cans	1.258	1.36	1.36	1.224	1.122	1.088
Other – brass and bronze	7.252	7.84	7.84	7.056	6.468	6.272
Other – bearing and bushings	2.479	2.68	2.68	2.412	2.211	2.144
Other – terne plate	2.146	2.32	2.32	2.088	1.914	1.856
Cable sheathing	**91**	**80**	**78**	**61**	**42**	**35**
Gasoline additives	**50**	**48**	**47**	**43**	**36**	**38**
Miscellaneous	**72**	**68**	**69**	**69**	**62**	**65**
Total	**1463**	**1533**	**1603**	**1551**	**1540**	**1574**

Table 3.2: The main function fulfilled by lead in batteries applications

Batteries	Lead type	Industry	Function fulfilled by lead
SLI batteries – Cars	Lead-antimony Lead oxide	Motor Vehicles industry	Conductivity Corrosion resistance
Motive power (traction) electric vehicles	Lead-antimony Lead oxide	Power industry	Conductivity Corrosion resistance
Industrial standby & power storage batteries	Lead-antimony Lead oxide	Power industry	Conductivity Corrosion resistance
Consumer – small electrical products	Lead-antimony Lead oxide	Power industry	Conductivity Corrosion resistance

Table 3.3: The main function fulfilled by lead in rolled and extruded applications

Rolled & extruded	Lead type	Industry	Function fulfilled by lead
Building materials (lead sheets) Proofing and flashing Shower pans Flooring	Pure lead or antimonial lead	Building industry	Corrosion resistance Rugged, flexible, long lasting, aesthetic appeal
Pipes	Chemical lead or antimonial lead	Chemical industry Plumbing and water distribution system	Corrosion resistance Flexibility
Radiation shielding materials	Pure lead or antimonial lead	Building industry	High density Radiation shielding
Sound proofing materials	Pure lead or antimonial lead	Building industry	High density Noise proofing
Chemical applications	Pure lead or antimonial lead	Chemical industry	Resists attack by a wide rang of chemicals Corrosion resistance

Table 3.4: The main function fulfilled by lead in pigments and other compounds

Pigments & other compound	Lead type	Industry	Function fulfilled by lead
Glass pigments - Cathode ray tube		Electronic industry Computers and TV	High density- radiation shield
Glass pigments – Crystal	Lead oxide	Glass industry	It adds lustre, density, and brilliance to the glass
Other – Plastic additives	Tri-and tetrabasic lead sulphate Basic lead carbonate	Plastic industry	Extend the temp. range at which the PVC can be processed without degradation
Other – Paints	Red lead Lead chromate Lead molybdate		Corrosion resistance
Other – Ceramics	Red lead Lead silicate		Lower melting point Wider softening range Low surface tension Good electrical properties Hard wearing Impervious finish

Table 3.5: The main function fulfilled by lead in alloys

Alloys	Lead type	Industry	Function fulfilled by lead
Solder – electronics	Tin-lead		Low melting point
Other – terne plate (terne coating)	Lead with 3 to 15% of Sn	Steel industry	Solderability Corrosion resistance

Table 3.6: The main function fulfilled by lead in cable sheathing applications

Cable sheathing	**Lead type**	**Industry**	**Function fulfilled by lead**
Electricity building	Chemical lead Antimony lead and arsenical lead	Power and communication	Protection against corrosion and moisture. Provide a mechanical protection of the isolation
Electricity outdoor	Chemical lead Antimony lead and arsenical lead	Power and communication	Protection against corrosion and moisture. Provide a mechanical protection of the isolation
Telephone outdoor	Chemical lead Antimony lead and arsenical lead	Power and communication	Protection against corrosion and moisture. Provide a mechanical protection of the isolation
Gas pipes outdoor	Chemical lead Antimony lead and arsenical lead	Power and communication	Protection against corrosion and moisture. Provide a mechanical protection of the isolation

3.2.1.2 Quantitative analysis of the inflow in substance stocks

In this step, the main applications that are sharing the same function are collected in one group. For each group, the amount of consumed lead will be calculated.
Table 3.7 shows the main three functions of lead and the applications which lead has been used in due to this function. Table 3.8, 3.9, and 3.10 show the total amount of lead consumed due to its high density high corrosion resistance and conductivity.

Table 3.7: The main three function of lead and the applications where it has been used

Conductivity	**Corrosion resistance**	**High density**
SLI batteries	SLI batteries	Radiation shielding material
Traction battery	Traction battery	Sound proofing material
Industrial battery	Industrial battery	Cathode ray tube
Consumers battery	Consumers battery	Crystal
	Lead sheets	
	Pipes	
	Chemical applications	
	Paints	
	Terne plate (coating)	
	Cable sheathing	

Table 3.8: Consumption of lead due to its high density

Year	Radiation Shielding	Sound Proofing	Cathode Ray Tube	Crystal Glass	Total
1993	21.4	6.42	81.403	31.262	140.485
1994	21.8	6.54	82.606	31.724	142.67
1995	23.4	7.02	84.611	32.494	147.525
1996	22.1	6.63	78.596	30.184	137.51
1997	22.2	6.66	80.601	30.954	140.415
1998	23.3	6.99	77.393	29.722	137.405

Table 3.9: Consumption of lead due to its high corrosion resistance

year	Batteries	Lead Sheets	Pipes	Chemical Applications	Paint	Plate	Cable Sheathing	Total
1993	743	171.2	0	10.7	9.338	2.146	91	1027.384
1994	822	174.4	0	10.9	9.476	2.32	80	1099.096
1995	869	187.2	0	11.7	9.706	2.32	78	1157.926
1996	870	176.8	0	11.05	9.016	2.088	61	1129.954
1997	888	177.6	0	11.1	9.246	1.914	42	1129.86
1998	919	186.4	0	11.65	8.878	1.856	35	1162.784

Table 3.10: Consumption of lead due to its conductivity

year	Batteries	Total
1993	743	743
1994	822	822
1995	869	869
1996	870	870
1997	888	888
1998	919	919

4 UNCERTAINTY IN STOCK MODELLING

By definition, models are a representation of the essential aspects of a system, which represent knowledge of that system in a usable form. This reflects that not everything is included and as a consequence the model might have a doubtful outcome. Uncertainty analysis is normally performed to make a statement about uncertain models and the reliability of their outcomes. Uncertainty analysis and sensitivity analysis are related but have a different purpose. Uncertainty analysis is performed to obtain insight in the noise of the model and, if possible, eliminate this. The purpose of sensitivity analysis is to detect which parameters and variables have a large influence on the noise in the outcomes. This gives insight on where best to put in the effort to look for more reliable data.

In this section, the following aspects will be treated:

- a description of existing methods for uncertainty analysis and their advantages and drawbacks;
- a description of the product stock system in a mathematical form;
- a description of the sources of uncertainties in the product stock system and the way to treat them;
- an application to the case of cathode ray tubes.

4.1 Existing methods for estimation the uncertainty in models

There are several estimators cab be used to estimate the parameters or the stochastic terms in the models. In this section, three of these will be mentioned namely, the least square estimator, Kalman filter and Monte Carlo approach.

Weighted least-square estimator

On the basis of reasonable arguments, the estimate of x can be found from a minimization of the criterion function of the form

$$\mathbf{V(x) = (y-Cx)^T R^{-1} (y-cx)}$$

where $\mathbf{R^{-1}}$ is a positive definite weighting matrix.

The estimate is given by

$$\mathbf{X = [C^T R^{-1} C]^{-1} C^T R^{-1} y}$$

If R is chosen to be equal to the covariance matrix of the zero mean observation error, the WLS estimate is the MARKOV estimate.

The error covariance matrix of the estimates can be calculated from

$$\mathbf{\Sigma = E\ [\ [C^T R^{-1} C]^{-1} C^T R^{-1} (cov\ v)\ R^{-1}C[C^T R^{-1} C]^{-1}\ ]}$$

which for cov **v** = R and C deterministic.

$$\Sigma= [C^T R^{-1} C]^{-1}$$

For ordinary least-squares estimation with weighting matrix R=I and output uncertainty v with constant variance, the error covariance matrix becomes:

$$\Sigma= \sigma^2 [C^T C]^{-1}$$

Kalman Filter (KF)

Kalman filter is used normally for Bayesian models which assume the stochastic term is known or partially known.

$$X' = f (x, u) + Gw$$
$$y_k = g (x_k) + v$$

Assumption
f, g, G are known
var x(0) = P_0 , var w = Q, var ν = R

1- Calculate the prediction or a prior estimates ($X^{\wedge}$)
2- Calculate the error covariance of the prediction ($P^{\wedge}$)
3- Calculate Kalman gain (K)
4- Calculate the error covariance (P)
5- Calculate the state estimate (correction step)

The advantage of Kalman filter is the possibility of predicting a future value of the estimates due to the validity of step 4 (the equation for calculating the covariance matrix of the error). The limitation of the filter is the assumption on Q and R.

Monte Carlo Approach

In lack of sufficient data needed for the WLS, or KF, Monte Carlo approach might be an option. Monte Carlo approach belongs to the unknown – but – bounded stochastic terms which assume that the uncertainty term belongs to a set.

The procedure in Monte Carlo approach is as follow:

1- Establishing acceptable behaviour of the state or the output from available quantitative and qualitative knowledge (output or state space);
2- Define a feasible parameter range from a prior knowledge;
3- Take random sample from this space (parameter space);
4- Run the model for each sample parameter;

5- Classify each parameter run as compliance with behaviour of the data or not producing the behaviour.

4.2 Description of the dynamic stock model in a mathematical form

In order to be able to perform an uncertainty analysis, the system under study must be described in a mathematical form. This is the purpose of Section 4.2. The product stock system as described qualitatively in Section 2, in reality contains three mathematical models:

- the leaching model, describing losses from the stock during use due to corrosion, volatilisation etc. etc., as a fraction of the stock itself;
- the delay model, describing the discarding of used products as a function of the past inflow and a certain delay;
- the inflow model, describing the past and future inflow of new products into the stock as a function of explanatory variables such as GDP, population etc. (see Section 3).

These three models will be described mathematically in the section 4.2.1, 4.2.2 and 4.2.3 respectively.

4.2.1 The leaching model

The leaching model describes the outflow as a fraction of the stock and can be written in two forms, a continuous state space form and discrete time form. The latter is normally used in practice.

Deterministic – continuous model

The outflow out of the consumption phase is given by the following equation:

$$F^{out}(t) = \gamma * S(t) \qquad (1)$$

γ is the leaching factor and S is the stock.

The stock is represent the state in the model and can be written in a state space form in the following form.

$$S' = F^{in}(t) - \gamma * S(t) \qquad (2)$$

Equation 2 can be rewritten in the following form:

$$S' = - \gamma * S(t) + F^{in}(t) \qquad (3)$$

The solution of equation 3 is given as the following:

$$\mathbf{S(t) = e^{-\gamma t} * S(0) + \int e^{-\gamma(t-\iota)} * F^{in}(\iota)\, d\iota}$$

To solve for S, S(0), and F^{in} are needed.

Deterministic - Discrete time model

The discrete time representation of the model is given by equation 4, 5.

$$S(t_{k+1}) = e^{-\gamma\Delta t} S(t_k) + [F^{in}(t_{k+1}) - F^{in}(t_k) / \Delta t] \, {}_0\!\int^{\Delta t} e^{-\gamma\iota} \, d\iota \quad (4)$$

$$F^{out}(t_k) = \gamma \; s(t_k) + D \, [F^{in}(t_{k+1}) - F^{in}(t_k) / \Delta t] \quad (5)$$

With $\Delta t = 1$

4.2.2 The delay model

The continuous time state representation is not very suitable to represent time delay. This because time delay represent a memory function which requires an finite number of states. The fixed time delay do not offer very large difficulties in simulation, because the output can simply be shifted backwards.

$$F^{out}(t) = F^{in} (t - L) \quad (6)$$

L is the life span of the product and can be modelled as an average life span or a life span distribution. Possible distributions are Normal Distribution, Weibull Distribution or Beta Distribution.

4.2.3 The linear regression model for the inflow

The linear regression model can be written in the following form:

$$y(t_k) = \Phi(t_k) \, \theta(t_k) \quad (7)$$

and can be written in a vector matrix form:

$$y = \Phi \, \theta \quad (8)$$

y = y(1), y(2), y(3)
Φ regressor matrix
θ parameter vector

4.3 General description of uncertainty sources and representation

4.3.1 Sources of uncertainty

Many sources of uncertainties may exist in a model. In general, there are three types: disturbance, errors and perturbation and unknowable future inputs.

External uncertainty: disturbance

Disturbance arises from uncertainties in the data external to the model, or the model inputs. Examples are:

- Uncertainties from unmeasured inputs or inputs not accounted for;
- Uncertainties arising from modelling from the first principles, i.e. using other knowledge about the system than measured inputs, such as an application of mass balance. There may be uncertainties in the original equation, or in the additional relations

Internal uncertainty: errors and perturbation

Perturbation arises from uncertainties in parameters within the model, for example:

- Special discretization error, lumping error, approximation error, averaging;
- Process errors and perturbations, neglect of variables, aggregation of entities.

In forecast mode: unknown future inputs

Last but not least, forecasting is a very uncertain business since the future cannot be measured, and all model outcomes are somehow projections of present and therefore by definition outdated knowledge. This puts a severe limit to the purposes that forecasting models can be used for. Typical sources of uncertainty in this area are:

- Disturbances modelling: realization of identified stochastic model;
- Future input modelling: time series models, sub-models, scenarios.

4.3.2 Representation of uncertainty in the model

Disturbances, inputs

The basic idea is to include the disturbances both in the system equation as well as in the output equation. If the system and its output are described by equation 9, 10

$$X' = f(x, u; \theta) \tag{9}$$
$$y = g(x, u; \theta) \tag{10}$$

then the uncertainty could be added to the system equation and the output equation as shown in equations 11, 12.

$$X' = f(x, u, w; \theta) \tag{11}$$
$$y = g(x, u, v; \theta) \tag{12}$$

Where w, ν are zero mean white processes (i.e. uncorrelated in time), often the assumption is made that w, ν enters the equation in addition term as shown in equations 13,14.

$$X' = f(x, u; \theta) + Gw \qquad (13)$$
$$y = g(x, u; \theta) + v \qquad (14)$$

For the linear systems the following form can be used:

$$X' = Ax + Bu + Gw \qquad (15)$$
$$y = Cx + Du + v \qquad (16)$$

where, A, B, C, D, G are possibly time-variant matrices.

The statistical properties of w, ν may be described either in probabilistic terms, or as a set, i.e. unknown-but-bounded. in both cases the model are non-deterministic.

Perturbations, structure/parameter

In this case the uncertainty is either expressed as structured, i.e. uncertainty in the parameters of the system.

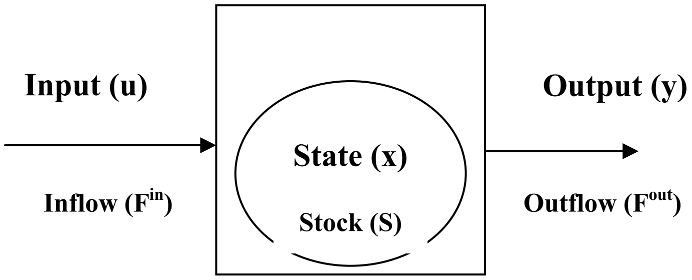
$$X' = f(x, u; \theta+\Delta\theta) \qquad (17)$$
$$y = g(x, u; \theta+\Delta\theta) \qquad (18)$$

or as unstructured, i.e. uncertainty of the equations or properties of the equations (e.g. system transfer function).

In the perturbation approach, the perturbation are not normally viewed as stochastic process but rather as selections out of the population of possible values. it is possible to describe the populations either in probabilistic terms or in the form of sets. in both cases, the model are non-deterministic.

4.4 Uncertainties in the dynamic stock models

In general, the system is described by its state, input, and output. Stocks in the consumption phase as shown in the figure below is the state, the input is the inflow of goods and the output is the outflow or the discarded goods.



In dynamic stock modelling, uncertainty does exist and could be from many sources. In this part of the report, an introduction to a possible uncertainty analysis of the dynamic stock model is given. In our product stock model, the uncertainties may come from different sources, related to the three submodels of the system and could be due to disturbances in the model or due to perturbations and errors or future inputs.

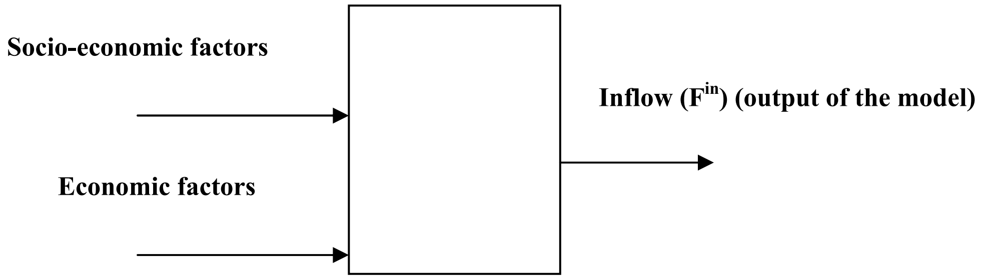
The disturbances are coming from the dynamics in the original equation (equation 3) as well as the additional relations of the input and/or the output (F^{in} and F^{out} in equation 3). The input or the inflow in the model is represented by a regression model. The regression model describing the present and future inflow of new products into the stock. The explanatory variables may not be correct or may be incomplete. For the future, major changes may happen limiting the applicability of the equation. Some variables may lose importance over time, while others may become more important.

The perturbations are due to parameter uncertainty.

1. The leaching model describing losses from stock during use. There may be uncertainties in the estimate of the annual loss fraction γ: this fraction may in fact be higher or lower, it may depend on the circumstances, or may be subject to change over time.

2. The delay model describing the discarding of used products. The estimate of the average life span may be incorrect or liable to change over time, as it has for example in the case of lead batteries. The chosen type of life span distribution may be incorrect, or the estimates for minimum and maximum.

The inflow of goods or the input into the consumption system (F^{in}) could be seen as output of another model and determined mainly by socio-economic factors such as GDP, Population and economic factors such as the income substitution and the price. These variables in a mathematical sense are states and the inflow of goods is the output of the regression model. We use the Least Square method of uncertainty analysis in the regression model of the inflow.



In the next sections, a description is given of a possible treatment of these uncertainties using the Least Square estimator. We draw on the mathematical description of the submodels as presented in Section 4.2.

4.4.1 Uncertainty in the leaching model, deterministic continuous time

As has been mentioned above, the uncertainty could be due to disturbances which is mainly coming from the input to the system or due to perturbation which is coming from the parameter (the leaching factor) in the system. In this section both will be represented in the mathematical equations.

Disturbances:

$$S' = - \gamma * S(t) + F^{in}(t) + Gw$$
$$F^{out}(t) = \gamma * S(t) + v$$

Perturbations:

$$S' = - (\gamma + \Delta\ \gamma) * S(t) + F^{in}(t)$$
$$F^{out}(t) = (\gamma + \Delta\ \gamma) * S(t)$$

Future inputs:

The sources of uncertainty are coming from the identified stochastic processes, time series, sub-models, and scenarios. The representation of the uncertainty in both the state equation and the output equation is the same as in the case of disturbances.

4.4.2 Uncertainty in the leaching model, deterministic discrete time

Disturbances:

$$S(t_{k+1}) = e^{-\gamma} S(t_k) + [F^{in}(t_{k+1}) - F^{in}(t_k)] \int_0^1 e^{-\gamma\iota}\, d\iota + G(t_k)\, w(t_k)$$

$$F^{out}(t_k) = C\, s(t_k) + D\, [F^{in}(t_{k+1}) - F^{in}(t_k)] + v(t_k)$$

In a simplified form

$$S(k+1) = e^{-\gamma} S(k) + [F^{in}(k+1) - F^{in}(k)] \int_0^1 e^{-\gamma\iota}\, d\iota + G(k)\, w(k)$$

$$F^{out}(k) = C\, s(k) + D\, [F^{in}(k+1) - F^{in}(k)] + v(k)$$

Perturbations:
The same formula can be used but now to introduce the uncertainty in the parameters.

4.4.3 Uncertainty in the delay model

Equation error structure

$$F^{out}(t) = F^{in}(t - L) + e(t)$$

e(t) is a white-noise term, i.e. a realization of the white-noise process {e}. The white noise is independent normally distributed variable with a zero mean. This shows that the noise at the output will be white if we generate the prediction from the previous measured outputs, but not if we generate the prediction from a sequence of predicted y's assuming e = 0.

Output error structure

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

If it is assumed that the process it self is noise free, i.e. producing noise free output z, and there are only white measurement noise disturbances on the measured output y, we would have the model

$$Z(t) = F^{in}(t - L)$$

$$F^{out}(t) = Z(t) + e(t)$$

We can eliminate the unknown Z and obtain the form

$$F^{out}(t) = F^{in}(t - L) + e(t)$$

4.4.4 Uncertainties in the estimation of the parameters in the inflow regression model

For the inflow of products to the consumption phase, the following deterministic form can be used:

$$y(t_k) = \Phi_0(t_k) + \Phi_1(t_k)\ \theta_1(t_k) + \Phi_2(t_k)\ \theta_2(t_k) + \Phi_3(t_k)\ \theta_3(t_k)$$

y = y(1), y(2), y(3), **The inflow of goods to the consumption phase**
Φ regressor matrix
θ parameter vector, GDP, Population and T

It is possible to introduce the error term in the equation as shown below

$$y(t_k) = \Phi(t_k)\ \theta(t_k) + e(t_k)$$

with k=1:N

In a vector matrix form the following equations can be used:

$y = \Phi\,\theta + e$

$y(t_1) = \Phi_0(t_1) + \Phi_1(t_1)\,\theta_1(t_1) + \Phi_2(t_1)\,\theta_2(t_1) + \Phi_3(t_1)\,\theta_3(t_1) + \nu(t_1)$
$y(t_2) = \Phi_0(t_2) + \Phi_1(t_2)\,\theta_1(t_2) + \Phi_2(t_2)\,\theta_2(t_2) + \Phi_3(t_2)\,\theta_3(t_2) + \nu(t_2)$
$y(t_3) = \Phi_0(t_3) + \Phi_1(t_3)\,\theta_1(t_3) + \Phi_2(t_3)\,\theta_2(t_3) + \Phi_3(t_3)\,\theta_3(t_3) + \nu(t_3)$

$y(t_n) = \Phi_0(t_n) + \Phi_1(t_n)\,\theta_1(t_n) + \Phi_2(t_n)\,\theta_2(t_n) + \Phi_3(t_n)\,\theta_3(t_n) + \nu(t_n)$

Below, a translation is made to the equation we use to describe the inflow into the product stock and a procedure for the estimation of the parameters is made based on the least square method.

$y(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \beta_3 x_3(t) + \varepsilon(t)$

y(t) is the inflow at time t
$\beta_0, \ldots\ldots \beta_3$ are the regression coefficients
$x_1, \ldots\ldots x_3$ are the independent variables

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ \\ y_n \end{pmatrix} = \begin{pmatrix} 1 & x_{1,1} & x_{2,1} & x_{3,1} \\ 1 & x_{1,2} & x_{2,2} & x_{3,2} \\ 1 & x_{1,3} & x_{2,3} & x_{3,3} \\ \\ 1 & x_{1,n} & x_{2,n} & x_{3,n} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \\ \varepsilon_n \end{pmatrix}$$

$y \;=\; X * \beta + \varepsilon$

To estimate the regression coefficient (β) the following form is used
$y = x * \beta$

$\beta = inv\,(X' * X) * X' * y$

To estimate the error in the regression form (ε)

$\varepsilon = y - X * \beta$

$\sigma^2 = 1/\,(n-4) * \varepsilon' * \varepsilon$

The error covariance matrix (P_β) is given by
$P_\beta = cov\,\beta = \sigma^2 * inv(X' * X)$

The covariance matrix can be used to estimate the uncertainty in the model in the future.

To estimate y in the future, the regression coefficient (β) estimated for the past can be used in combination with the projected value for the elements in the X matrix.

$$yn = Xn * \beta$$

The covariance matrix for the new prediction is given by the following equation
$Pyn = Xn * cov\ \beta * Xn'$

Pyn defines the error propagation from an uncertain x to the output y.

4.5 Application to the case of cathode ray tubes (CRT's)

It is possible to represent the CRT system in matrix form as below:

$$y(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \beta_3 x_3(t) + \varepsilon(t)$$

$$\begin{pmatrix} 120.44 \\ 130.67 \\ 158.61 \\ \\ 263.11 \end{pmatrix} = \begin{pmatrix} 1 & 4047 & 361.18 & 1 \\ 1 & 4145 & 362.90 & 2 \\ 1 & 5101 & 364.55 & 3 \\ & & & \\ 1 & 7817 & 376.32 & 13 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \\ \varepsilon_{13} \end{pmatrix}$$

y(t) is the observed inflow of CRT's at from 1988 through 2000 (see appendix A)
β_0,….. β_3 are the regression coefficients
x_1, …. x_3 are the independent variables, GDP, population, and T (see appendix A)

To estimate the regression coefficient (β) associated with GDP, population and T, the following form can be used:

$$\beta = inv\ (X' * X) * X' * y$$

$$\beta = \begin{pmatrix} 9.2246 \\ 0.001 \\ -0.254 \\ 0.0371 \end{pmatrix}$$

The estimated inflow is given by the following equation:
$$yc(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \beta_3 x_3(t)$$

The estimated error is given by the following equation:
$$\varepsilon(t) = y(t) - X(t) * \beta$$

$$\boldsymbol{\varepsilon} = \begin{pmatrix} -17.512 \\ -2.1376 \\ 16.762 \\ 23.761 \\ \\ 9.9248 \end{pmatrix}$$

The error covariance matrix (P_β) is given by:

$$\boldsymbol{P_\beta = \mathrm{cov}\,\beta = \sigma^2 * inv(X'{*}X)}$$

$$\boldsymbol{\sigma^2 = 1 / (n - 4) * \varepsilon'{*}\,\varepsilon}$$

$$\sigma^2 = 1/ (13 - 4) * \varepsilon'{*}\,\varepsilon$$

$$\sigma^2 = 385.922$$

$$\textbf{cov}\,\boldsymbol{\beta} = \begin{pmatrix} 1.7499 & 0 & -0.0049 & 0.0049 \\ 0 & 0 & 0 & 0 \\ -0.0049 & 0 & 0 & 0 \\ 0.0049 & 0 & 0 & 0 \end{pmatrix}$$

Figure 4.1 shows the difference between the measured inflow and the calculated inflow before and after the introduction of the error term and the error variance with time.

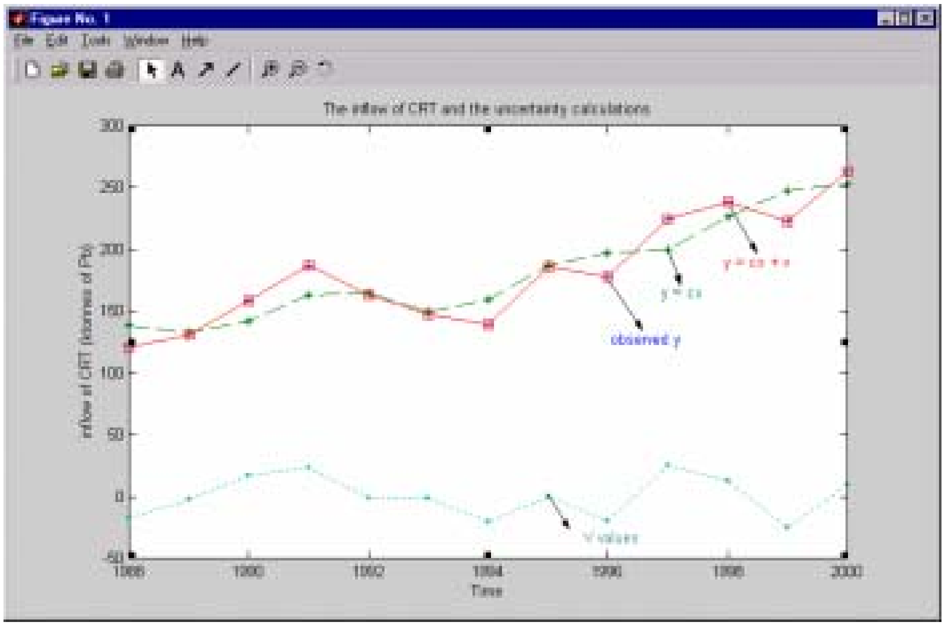


Figure 4.1: Comparison between the observed inflow and the inflow calculated from the regression model before and after the uncertainty analysis.

5 CASE STUDY - LEAD IN THE EU

5.1 Introduction

In this chapter, the dynamic substance stock model as described in chapter 3 will be implemented to the substance lead as a case study. In fact, the original aim was to study and implement the model for the lead in the European Union (EU15). We started with two of the lead applications, namely, the starting, lighting and ignition (SLI) batteries and cathode ray tubes (CRT's). However, it was not possible to complete this case study on the European level due to the difficulties associated with the data availability and collection. For this reason, we shifted to the national level and elaborated a case study for lead in the Netherlands. The results are shown in Chapter 6. Because some general aspects of the implementation of the model are illustrated by the two lead applications at the EU level, we chose to keep the incomplete EU case study in the report after all.

Lead enters the stock of products-in-use through its different applications. These applications enter the economy either through the production and trade of the lead containing products or through the trade of other product that contains these lead products. The production figures of the lead containing products in the EU can be obtained from the international lead and zinc study group (ILZSG, 1999), however, the trade figures which can be obtained for the EU countries from the Eurostat database were difficult to obtain due to the EU enlargement in the study period. Although, it is possible to get these figures from the national statistics of the countries which joined the EU recently, this option was difficult and time consuming because different countries organise their statistics differently (different products codes and aggregation).

Due to the difficulties associated with the data collection, the model implementation and verification was shifted to the case of lead in the Dutch economy as data collection became slightly easier. This case study will be described completely in chapter 6. In this chapter the model as applied to the SLI batteries and CRT's on the EU level will be given as an example.

In section 5.2, general information on the use of lead in the economy will be mentioned and in section 5.3, the model as applied for the SLI batteries and cathode ray tubes will be described.

5.2 General information

5.2.1 The use of lead in the economic processes

Lead was one of the first metals used by humankind, and its use has been extensive through history. Nowadays lead is the most widely use metal after iron in our society. Its unique properties such as its corrosion resistance, its flexibility, its high density, and its low melting point (327°C) make it suitable for several applications.

Lead has been used in metallic form and as a compound. Lead compounds may be divided in two categories:

(1) organic lead compounds, such as tetraethyl lead and tetramethyl lead;
(2) inorganic lead compounds such as lead oxide, lead silicate, lead nitrate and others.

By far the most dominant use is its use in metallic form in batteries (73% of the world consumption). The second largest application is the lead use in compound form, especially as pigments and as stabiliser in plastics (11% of the world consumption). Third is the use of rolled and extruded lead (6% of the world consumption), for example in building applications. The main intentional applications of lead and the world consumption in 1997 are shown in table 5.1.

Beside its intentional use, lead is present in products as a contaminant. Products may contain lead due to the natural presence of lead in ores such as fertiliser and fossil fuels especially coal. Other lead contamination's have an anthropogenic origin such as lead in sewage sludge, manure and ashes and slags of the waste incineration and steel industry.
Due to the technological developments, increase in the global population, and other factors, the consumption of some lead applications is expected to increase such as batteries and lead sheet. Some application will remain constant such as extruded products, pigments, ammunition, and alloys. Some will be reduced or eliminated such as the use of lead for water pipes, lead stabiliser in plastics, cable sheathing, gasoline additives, and paints. The trend of some application is unclear such as solder.

Table 5.1: The main intentional lead applications

Application	Percentage (%)
Batteries	72.5
Rolled and extruded	6.1
Pigments and other compounds	10.9
Shot/ammunition	2.4
Alloys	2.4
Cable sheathing	1.7
Gasoline additives	0.9
Miscellaneous	3.1

The main processes, flows and stocks of lead in the economy are shown in figure 5.1.

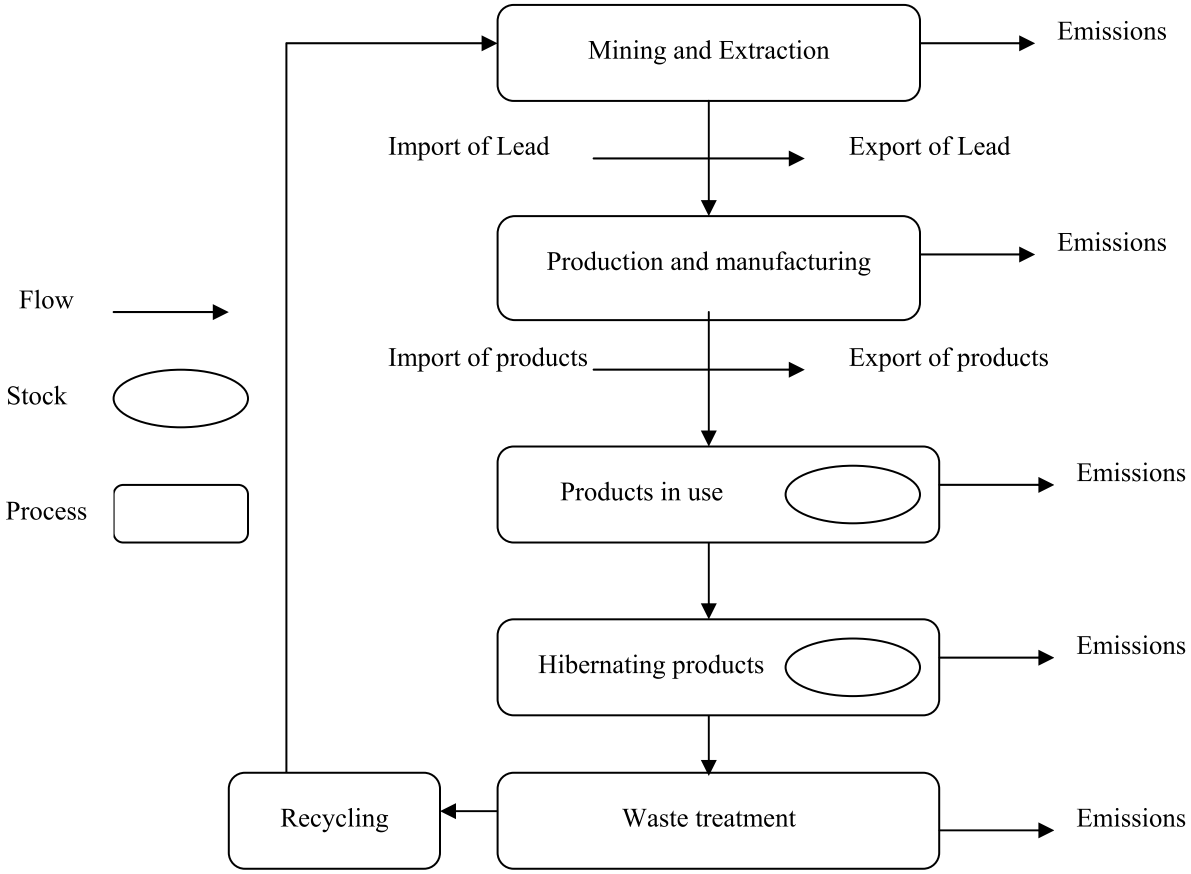


Figure 5.1: Lead processes, flows, and stocks in the economy

5.2.2 Classification of lead stocks

As mentioned in section 2.2, different classifications can be made for the stock. In this section this classification will be applied to the lead applications. Table 5.2 summarises this information.

Life span
The life span differs enormously among the various lead applications. For some application the life span could be 50 years or even longer, for example for lead sheet and pipes, while for other applications, the life span could be less than 5 years, as in the case of lead batteries and ammunition. Generally, the letters A,B, C, D will be used to indicate the range of life span of the lead applications: **1 < A < 5, 5 < B < 10, 10 < C < 20, D > 20**.

Recyclability
For some of the lead applications, such as a number of metallic applications like lead sheet and lead batteries, the recycling rate is very high. For other applications, no recycling system exists nor would this be feasible at present, which is the case for the

pigment and stabiliser applications. The letter **R** will be used for recycled and recyclable applications, **NR** for the non-recyclable applications.

Corrosion

Corrosion and slow leaching from the various lead applications and stocks may occur such as the corrosion from building material to soil and sewage system, ammunition to soil, while in some other applications this is not the case such as the batteries and pigments. In general the letter **P** will be used when corrosion in certain application is possible and **NP** will be used when corrosion is not possible

Trace/bulk

Trace applications refer to the products wherein lead is used only in small amounts, while bulk applications contain a relatively large amount of lead. This distinction has implications for the recoverability, and therefore the recyclability of the lead. Some of the lead applications can be characterised as "trace" applications, such as the use of lead in pigments, while other applications are "bulk" applications, such as the use of lead in batteries. The letter **T** will be used for those trace applications and the letter **B** for the bulk applications.

Hibernating

Some of the lead applications is phased out but still exist in the economic system. For example, water pipes is phased out but a large amount of lead pipes are still present in ‘old’ buildings and distribution systems. The letter **H** will be used for hibernating stocks and **U** for the stocks in use.

Intentional

Lead has many intentional use applications such as its use in batteries and pigments but beside the intentional use of lead, lead is also present in products as a contaminant for example in fossil fuels, fertiliser and agricultural products. The abbreviation **In** will be used for the intentional use of lead and the abbreviation **NI** for unintentional use.

Metallic/Compound

Lead has been used in a metallic form and as a compound. Lead compounds have been widely used as pigments in paint, stabilizer in PVC industry, and gasoline additives. Metallic use such as its use in alloys and others. The most common use of lead compounds are tetraethyl lead and lead oxide. The letter **E** will be used for applications of the element and the letter **C** will be used for applications as a compound.

Table 5.2: General classifications of lead stocks by application

Application	Life span	Recyclable	Corrosion	Trace/bulk	Hibernating
Batteries					
SLI batteries - Cars	A	R	NP	B	U
SLI batteries - Lorries	A	R	NP	B	U
SLI batteries - Trucks	A	R	NP	B	U
Motive power	A	R	NP	B	U
Industrial	B	R	NP	B	U
Consumer	A	R	NP	T	U
Rolled & extruded					
Building materials (lead sheets)	D	R	P	B	H
Pipes	D	R	P	B	H
Radiation shielding materials	C	R	NP	B	U
Sound proofing materials	C	R	NP	T	U
Chemical applications	C	R	NP	T	U
Collapsible tubes	C	R	NP	T	U
Wine bottle capsules	C	R	NP	T	U
Pigments & other compound					
Glass pigments - Cathode ray tube	C	NR	NP	B	H
Glass pigments – Crystal	C	NR	NP	T	H
Glass pigments - Optical glass	C	NR	NP	T	U
Glass pigments - Light bulbs	C	NR	NP	T	U
Other – Plastic additives	D	NR	NP	T	H
Other – Glazes	C	NR	NP	T	U
Other – Paints	C	NR	NP	T	H
Other – Ceramics	C	NR	NP	T	U
Shot and ammunition					
Sporting shot		NR	P	B	H
Steelmalding shot		NR	P	B	H
Alloys					
Solder – electronics	C	NR	P	T	H
Solder – plumbing	C	R	P	T	U
Solder – car radiators	C	R	P	T	U
Solder- car body	C	R	P	T	U
Solder – food cans	C	R	P	T	U
Other – brass and bronze	C	NR	P	T	U
Other – bearing and bushings	C	NR	P	T	U
Other – terne plate	C	NR	P	T	U
Cable sheathing					
Electricity building	D	R	P	T	H
Electricity outdoor	D	R	P	T	H
Telephone outdoor	D	R	P	T	H
Gas pipes outdoor	D	R	P	T	H
Gasoline additives					
Gasoline additives					
Miscellaneous					
Type metal	C	R	NP	T	
Wheel weights	C	R	NP	T	
Miscellaneous cast	C	R	NP	T	
Galvanizing	C	R	NP	T	
Annealing	C	R	NP	T	
Plating	C	R	NP	T	

Table 5.2 continued

Application	Intentional	Metallic/compound
Batteries		
SLI batteries – Cars	In	E
SLI batteries – Lorries	In	E
SLI batteries – Trucks	In	E
Motive power	In	E
Industrial	In	E
Consumer	In	E
Rolled & extruded		
Building materials (lead sheets)	In	E
Pipes	In	E
Radiation shielding materials	In	
Sound proofing materials	In	
Chemical applications	In	
Collapsible tubes	In	
Wine bottle capsules	In	
Pigments & other compound		
Glass pigments – Cathode ray tube	In	C
Glass pigments – Crystal	In	C
Glass pigments – Optical glass	In	C
Glass pigments – Light bulbs	In	C
Other – Plastic additives	In	C
Other – Glazes	In	C
Other – Paints	In	C
Other – Ceramics	In	C
Shot and ammunition		
Sporting shot	In	E
Steelmalding shot	In	E
Alloys		
Solder – electronics	In	E
Solder – plumbing	In	E
Solder – car radiators	In	E
Solder- car body	In	E
Solder – food cans	In	E
Other – brass and bronze	In	E
Other – bearing and bushings	In	E
Other – terne plate	In	E
Cable sheathing		
Electricity building	In	E
Electricity outdoor	In	E
Telephone outdoor	In	E
Gas pipes outdoor	In	E
Gasoline additives		
Gasoline additives	In	C
Miscellaneous		
Type metal	In	E
Wheel weights	In	E
Miscellaneous cast	In	E
Galvanizing	In	E
Annealing	In	E
Plating	In	E

5.3 Stocks of lead applications

In this section, a number of lead applications are analysed. The methodology as described in Section 3 is applied to lead product stocks of batteries (5.3.1) and cathode ray tubes (5.3.2). This will enable us to test the methodology and see whether it can be made applicable in practice. It also sheds some light on the required data and the difficulties we may encounter when looking for the relevant data.

5.3.1 Application of lead as a metal: lead batteries

By far the largest application of lead is the use of lead in batteries. Lead in batteries is applied in a variety of products:

- SLI batteries for petrol and diesel engine vehicles, cars, lorries and trucks;
- traction batteries to power electric vehicles;
- standby and storage batteries to provide emergency power in events of electrical failure;
- consumer batteries in small electrical products.

Table 5.3 shows the consumption of lead for the manufacture of batteries for different countries in the EU15. In this figures it is assumed that the consumption of batteries in the EU15 equals the production of batteries.

Table 5.3: The consumption of lead (ktonnes) for the manufacture of batteries in the EU15 in 1993-1998. (ILZSG, 2000)

Country	1993	1994	1995	1996	1997	1998
Austria	41.5	42.4	43.5	39.0	42.0	46.0
Belgium	21.4	19.8	19.8	14.9	15.5	14.0
Finland	3.0	3.5	3.5	3.5	3.5	3.0
France	155.8	170.4	189.9	190.9	188.2	199.0
Germany	204.1	215.7	206.9	192.7	178.4	181.7
Italy	109.0	132.0	149.4	158.4	165.6	174.7
Netherlands ^	18.0	26.0	29.0	25.0	25.0	24.0
Scandinavia	20.0	27.0	30.0	35.0	32.0	30.0
Spain	67.3	78.0	88.0	103.0	127.0	141.0
United kingdom	102.6	107.6	108.8	107.2	110.8	106.0
Total	742.7	822.4	868.8	869.6	888.0	919.4

^ includes cable sheathing from 1996 and onward

General information on batteries

Substitution

There are several alternatives to the lead-acid batteries, which can store electricity. These include nickel-cadmium, nickel metal hydride, lithium ion, polymer-based battery system, fuel cell, liquid gas, and hybrids which use a combination of fuel cell and liquid gas. All of these alternatives are more expensive than lead-acid batteries. Nickel-cadmium batteries are commercially available for some applications but can not replace the lead-acid batteries in all applications specially cars.

Reuse and recycling

Although the recycling rate of lead acid batteries is very high, the batteries still make a large contribution to the lead load of Municipal Solid Waste due to the large consumption of lead batteries. The collection rate of batteries is high in most of Western Europe. More recently, an EU batteries directive obliges Member States to ensure a high rate of battery collection. Different countries have approached this in various ways. Stated collection targets range from 100% in France, and 99.9% in Denmark, to 75% in Portugal. Some Member States like the UK, have not set up any formal system, as a high (estimated at 90%) recycling rate is already achieved by existing routes using scrap dealers (Scoullos, Vonkeman & Thorton, 2001). It is assumed that of the collected batteries, 100% of the lead is recovered and becomes available as secondary lead for new applications.

Life span

The lifetime of batteries in cars is estimated to be 4 to 5 years. For industrial applications the lifetime is about 10 years (Scoullos, Vonkeman & Thorton, 2001).

Starting, lighting, and ignition (SLI) batteries

All vehicles with a combustion engine are containing a battery which is used as the energy storage system for starting, lighting, and ignition. The automotive batteries are operating on the basis of the lead-acid/lead-oxide electrochemical system. Average weight of a car battery is 13 kg, with a lead content of 7.6 kg.
SLI batteries have been used in different products such as cars, trucks, and lorries. Figure 5.2 shows the processes, flows, and stocks of lead in different SLI batteries products.

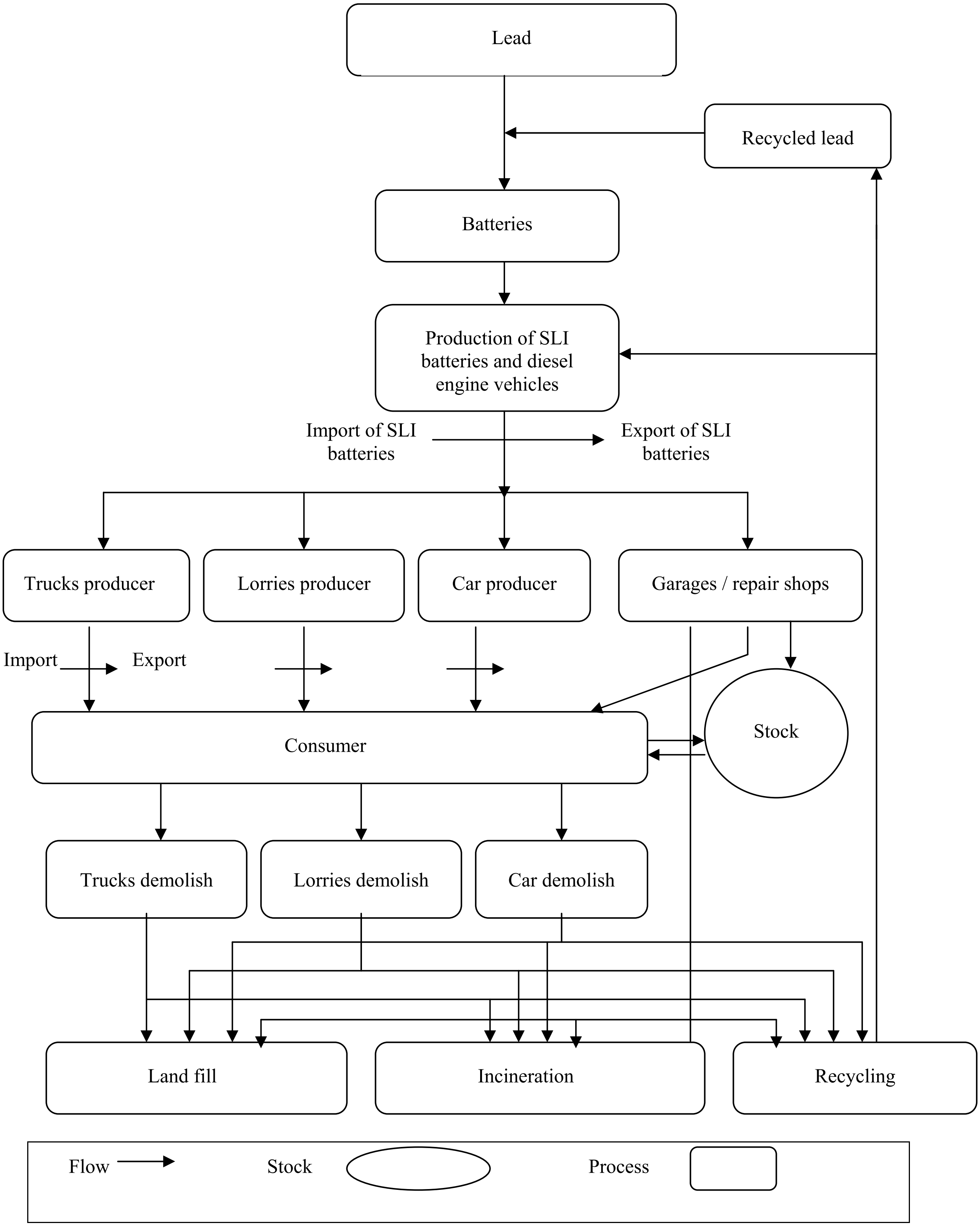


Figure 5.2: the lead processes, flows, and stocks in SLI batteries

5.3.1.1 The main variables in the system

The inflow of SLI batteries

The inflow of SLI batteries into the stock of consumption-and-use phase is the amount of SLI batteries produced inside the system plus the imported amount minus the exported amount. SLI batteries enters the economy either as a separate product or in combination with other products such as cars, lorries and trucks. When the inflow of SLI batteries to be calculated, the amount of batteries corresponding to the amount of these vehicles should be included.

The outflow of SLI batteries

The outflow of SLI batteries from the stock of consumption-and-use phase is the amount of the discarded SLI batteries. No emission during use of SLI batteries.

Waste treatment

The outflow from the consumption-and-use phase will be partly recycled and partly will end up in the final waste treatment either in the landfill sites or the incineration plants. The recycling percentage of SLI batteries is about 95% of the discarded batteries. The stream of final waste is split between landfill 80% and incineration 20%. These values are observed in the year 2000 (Tukker, 2001).

5.3.1.2 The main factors affecting the dynamic behaviour of the system – Product level

The inflow level

As has been mentioned in sections 2.4.1 and 3.1, several factors could effect the shape of the inflow curve. In the case of the inflow of SLI batteries, these factors could be:

- Population size;
- GDP and its sectoral share;
- Welfare;
- Income;
- Technological developments;
- Substitution.

Substitution

No practical alternative for lead starter batteries are known that would be available at a mass production level. Batteries based on NiMH and Li-ion have disadvantage in term of their technical functionality and the price of these might be more than twice that of lead-acid batteries.

Due to the modern electronic demand, it is expected to introduce the higher voltage system (42 V) in the cars electrical supply which may result in the introduction of two separate system batteries, one for starting and one for continuous electrical supply.
There are several technologies, which could be chosen for the 42 V system other than lead-acid such as NiMH, Li-ion or super capacitor cells.

The outflow level

The main factors determine the shape of the outflow are:

- Discarding of car, lorries, trucks(life span);
- Discarding of batteries (life span);
- Discarding of car, lorries, trucks (accidents);
- Discarding of batteries (broken).

Life span

The average life span of SLI batteries is from 4 to 5 years.

Corrosion

In the literature no emissions during the use of lead-acid batteries are reported. The most important leakage to the environment probably will take place in the disposal phase.

Recycling

A recycling system for lead-acid batteries is established in several countries since several years. A recycling percentage of 95% is projected for SLI batteries.

5.3.1.3 Modelling the inflow and outflow of battery stocks

Modelling the inflow stocks

To evaluate the effect of the influential factors on the inflow level, regression analysis is used. Statistical models give a quantitative insight on the relation between the dependent variable in the regression equation and the independent variables. In our case dependent variable is the inflow of SLI batteries into the consumption-and-use phase and the independent variables are Gross Domestic product (GDP), Population (Pop), and Time (T) which will be used as a proxy for other variables combined influence over time on the inflow trend. The structure in equation 1 has been used in the analysis. The period of analysis was from 1988 to 1999.

$$Y_t = \beta_0 + \beta_1 X_{1,t} + \beta_2 X_{2,t} + \beta_3 X_{3,t} + \varepsilon \qquad (1)$$

Y_t is the inflow at time t
$X_{1,t}$ is GDP at time t, $X_{2,t}$ is the population at time t, $X_{3,t}$ is the time (T), T=1 for the year 1988, T=2 for the year 1989, and so on

β_0, is the intercept, β_1, β_2, β_3 are the corresponding coefficients, and ε is an error term

Step 1: Establish correlation between the inflow curve and the parameters

Table 5.4: results of the analysis of the individual factors on the inflow of SLI batteries

Estimation	Variables	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	β_3 (t-value)	R^2	R^2adj	F- statistics
1	GDP	1408 (3.21)	0.09 (1.53)			0.19	0.11	2.348
2	Pop	-13168 (-1.8)		41.2 (2.1)		0.3	0.24	4.451
3*	T	1639 (9.36)			65.34 (2.75)	0.43	0.37	7.548

* significant at 95%
** significant at 99%

Table 5.4 shows the result of the relation between the inflow and GDP. Population and the time (T). Estimation 1 shows a positive correlation between the GDP and the inflow with a low coefficient of determination (R^2). The same for the population in estimation 2. Estimation 3 shows a positive correlation between the inflow and the time variable with a relative high (R^2). The correlation between the inflow of SLI batteries and the time variable is significant. This means the other factors included in the time variable (technological developments and substitution and maybe others) are more important than the GDP and the population on the inflow of SLI batteries. One thing for certain is that the substitution does not have any effect on the inflow because the coefficient β_3 has a high positive value and the inflow will always increase with the time.

Step 2: Establish the relative importance of the parameters

Table 5.5: results of the analysis of the combined factors on the inflow of SLI batteries

Estimation	Variables	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	β_3 (t-value)	R^2	R^2adj	F-statistics
4	GDP, Pop	-27861 (-1.456)	-0.13 (-0.831)	83 (1.53)		0.35	0.21	2.503
5*	GDP,T	2315 (4.703)	-0.15 (-1.458)		130 (2.61)	0.54	0.43	5.264
6**	Pop, T	112536 (4.418)		-307 (-4.354)	472 (4.994)	0.81	0.77	20.03
7**	GDP, Pop, T	145532 (4.097)	0.122 (1.287)	-400.26 (-4.0326)	545.18 (5.082)	0.85	0.79	14.881

* significant at 95%
** significant at 99%

It is clear from the estimations 4,5,6 that the combination between two independent variables is improving the overall correlation goodness. It is also clear that the most important combination is when the time variable is included. When estimation 5 and 6 to be compared, it is obvious that the combination between the time and population has a higher value for R^2 than the combination between the time and the GDP which lead to the fact that the population still has more influence on the inflow than the GDP. When all the independent variable are included in the regression equation (estimation 7), R^2 has the highest value. When estimation 6, and 7 to be compared, R^2 does not improved significantly by adding the GDP to the equation.

Step 3: Establish the relation between the important influential aspects and the inflow curve

The best regression model as a result from the analysis is when the three independent variables the GDP, Population and the time are included in the model. The following model will be used to calculate the inflow of the SLI batteries.

$$Inflow(t) = 145532 + 0.122\, GDP(t) - 400.26\, Pop(t) + 545.18\, T(t) \qquad (2)$$

Figure 5.3 shows the difference between the measured values of the inflow of SLI batteries and the calculated value of the inflow from the regression model in equation 2

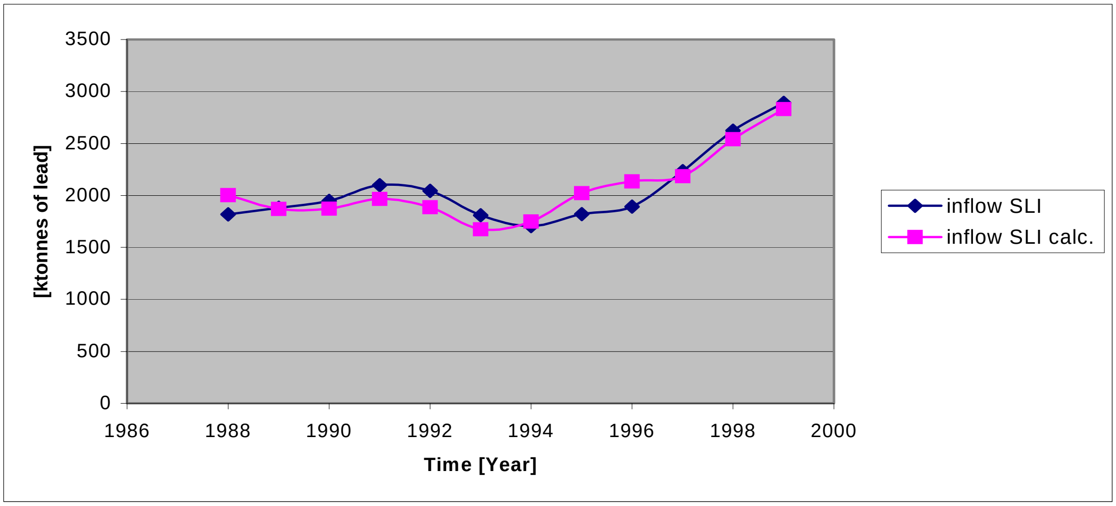


Figure 5.3: The difference between the measured and calculated inflow of SLI batteries

Modelling the outflow stocks

The outflow will be mainly determined by the discarding product. The life span of SLI batteries in the economic system assumed to be 4years. The outflow will be calculated according to equation 3. The results are shown in figure 5.4.

$$O(t) = I\,(t-L) \qquad (3)$$

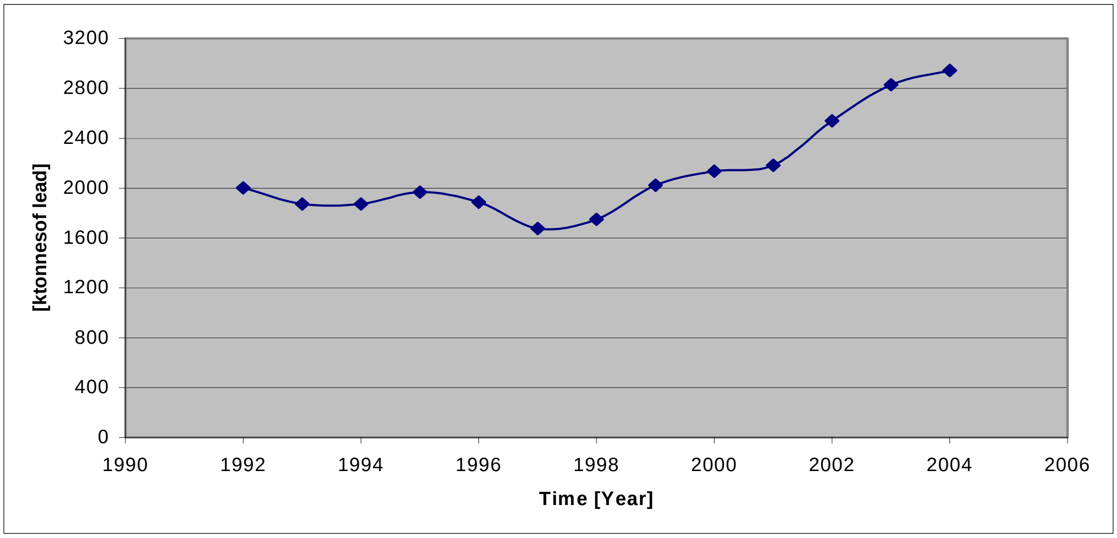


Figure 5.4: The outflow of SLI batteries.

5.3.2 Application of lead as a compound: cathode ray tubes

A considerable use of lead is the application of lead as pigment and stabiliser of plastics (PVC). Lead is used as a compound in a wide range of products including:

- Cathode ray tubes, as protection from harmful rays the tubes for television and computer monitors are constructed from a special glass, the glass composition of CRT faceplates contains heavy metals such as lead and other elements including arsenic and fluorine. The glass in cathode ray tube containing about 2 kg of lead in the form of lead silicate. Figure 5.5 shows the processes, flows and stocks of lead in CRT’s.
- Other glass applications, like lead crystal, radiation glass and optical glass,
- Stabiliser in PVC, lead compounds are added to PVC in order to prevent the plastics from degradation caused by heat and UV-light during the manufacture and use.
- Ceramic glazes, to provide a smooth, clear and scratch free finish to a variety of ceramic products,
- Lead paints, although no longer used in paints for use by the public, lead is still an important constituent of special paints used for such purposes as corrosion protection of steel, road markings and warning signs.

The largest current application for lead compounds is in cathode ray tubes. The second most important application for compounds is the use of lead as stabiliser in PVC. Table 5.6 shows the relative use of lead compounds in the different products (derived from OECD figures for 1990 (OECD, 1993)).

Table 5.6: The relative consumption of lead pigments and compounds in products

Pigments and other compounds	%
Glass pigments	
Cathode ray tube	40
Crystal	15
Speciality glass/optical	4
Light bulbs	3
Other pigments and compounds	
Plastic additives	23
Glazes	9
Paints	4
Ceramics	2

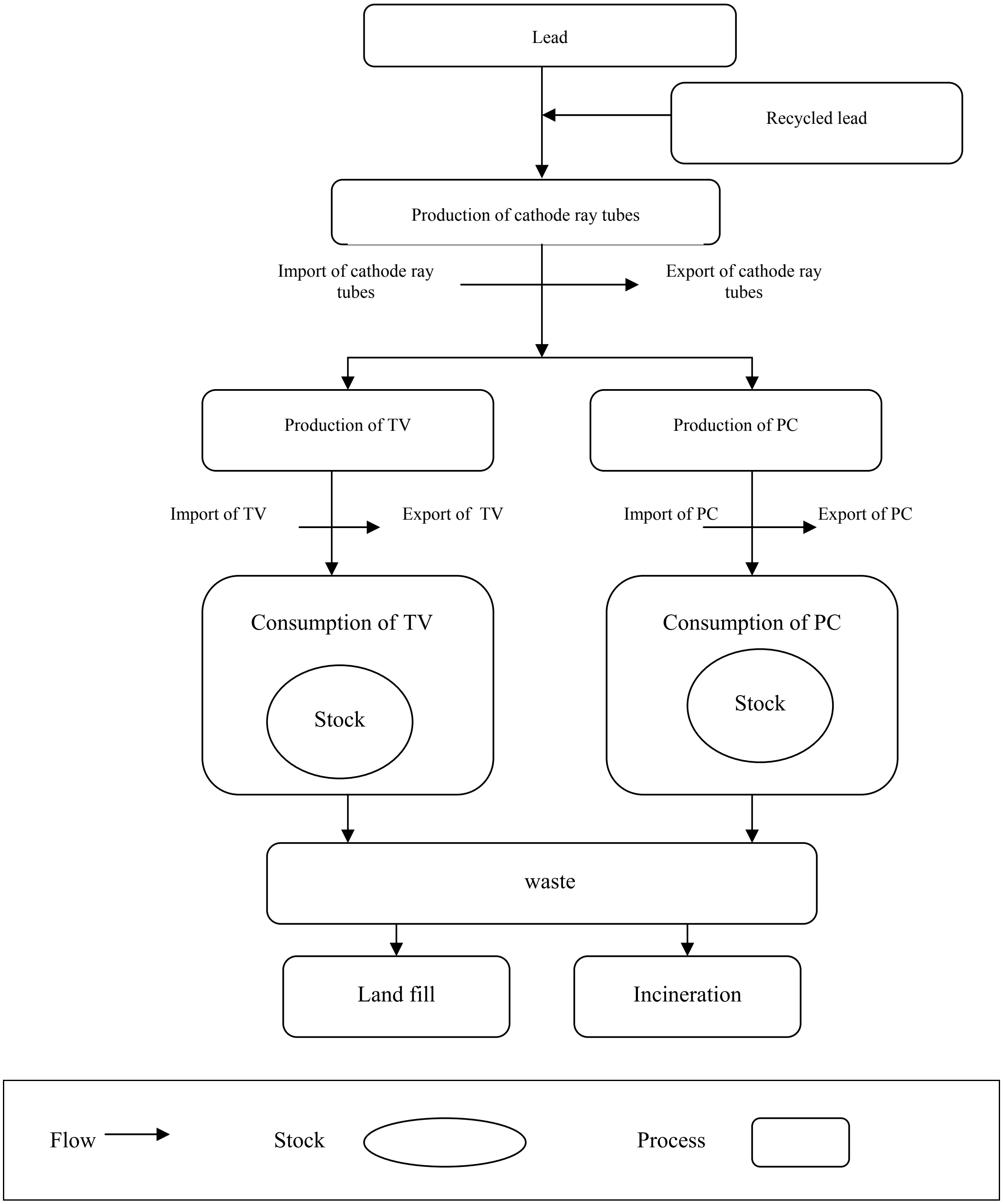


Figure 5.5: Processes, flows and stocks of lead in CRT's in the economy

5.3.2.1 The main variables in the system

The inflow of CRT’s

The inflow of CRT’s into the stock of consumption-and-use phase is the amount of CRT’s produced inside the system plus the imported amount of CRT’s minus the exported amount. CRT’s enter the economy either as a separate product or in combination with other products such as TV’s and computer monitors. When the inflow of CRT’s is to be calculated, the amount of tubes corresponding to the amount of these monitors and TV’s should be included.

The outflow of SLI batteries

The outflow of CRT’s from the stock of consumption-and-use phase is the amount of the discarded CRT’s plus the amount of discarded TV’s and monitors. No emission during use of CRT’s.

Waste treatment

The outflow from the consumption-and-use phase will end up in the final waste treatment either in the landfill sites or the incineration plants. No recycling scheme has been established for CRT’s. The stream of final waste is split between landfill 80% and incineration 20%. These values are observed in the year 2000.

5.3.2.2 The main factors affecting the dynamic behaviour of the system – Product level

The inflow level

As has been mentioned in sections 2.4.1 and 3.1, several factors could effect the shape of the inflow curve. In the case of the inflow of CRT’s, these factors could be:

- Population size;
- GDP and its sectoral share;
- Welfare;
- Income;
- Technological developments;
- Substitution.

Factors such as population, GDP, welfare, and income are described in section 2.4.1. In the case of CRT’s, however, it is important to mention more specific information about the factors substitution and technical developments.

Substitution and technical developments

Lead additions give excellent shielding properties to glass. No viable alternatives are known of at present. Some researcher indicates that it could be possible to replace the lead with other materials such as barium, strontium, and zirconium but no such a glass is commercially available and it is not known if these materials can be supplied in sufficient quantities to meet demand. The lead demand for cathode ray tubes reflects the increase in demand for television and computer terminals. It is likely that the use of cathode ray tubes will decline as a result of the advent of flat screen displays. It is very hard to predict how fast such displays will totally remove cathode ray tubes from the market.

The outflow level

The main factors determine the shape of the outflow are:
- Discarding of cathode ray tubes (life span);
- Discarding of TV (life span);
- Discarding of PC (life span).

Life time

The lifetime of a cathode ray tube is about 15 years.

Emissions and corrosion

In the literature no emissions during the use of pigments and other compounds are reported. The most important leakage to the environment probably will take place in the disposal stage of the products containing pigments or stabiliser. Lead in glass is assumed to be immobile and will therefore not lead to emissions in the incinerator and on the landfill sites..

Recycling

None of the products containing pigments and stabilisers are assumed to be recycled. The main source of lead in cathode ray tubes is from TV sets and computer monitors. Very little recycling is done in Europe at present. However for the future recycling rates for electrical and electronic equipment are predicted to increase. Leaded glass could be returned to glass manufacturers for recycling. At present , the glass industry is not doing this because there is no economic incentive to do so (Scoullos, Vonkeman & Thorton, 2001). It is likely that the EU's proposed Directive on Waste Electrical and Electronic Equipment (WEEE) will improve this situation. It is difficult to derive targets, however. The current draft of the directive suggests that a collection rate of 4 kg/inhabitant for WEEE should be reached. The WEEE this absolute value rather than a collection percentage, since the total amount of WEEE in the EU is not clear. Dutch data (134,000 tpa disposed (VROM, 2000), 16 million inhabitants) suggest an amount of 8.5 kg WEEE per inhabitant, implying that the EU target would mean a collection rate of some 50 %. The draft WEEE states that of equipment with cathode ray tubes that have been collected

75% should be recycled or recovered. With a collection rate of 25 % or 50 % this implies overall recycling rates of 19 to 37.5 %, assuming that for cathode ray tubes average collection rates and average recycling rates will be applicable. Dutch data suggest that for the main sources of cathode ray tubes (TVs, monitors) actually very good collection rates can be achieved.

5.3.2.3 Modelling the inflow and outflow of CRT's stocks

Modelling the inflow stocks

The same analysis in section 4.3.1.3 is used for the CRT inflow case. The structure of equation 4 is used.

$$Y_t = \beta_0 + \beta_1 X_{1,t} + \beta_2 X_{2,t} + \beta_3 X_{3,t} + \varepsilon \qquad (4)$$

Y_t is the inflow at time t

$X_{1,t}$ is GDP at time t, $X_{2,t}$ is the population at time t, $X_{3,t}$ is the time (T), T=1 for the year 1988, T=2 for the year 1989, and so on

β_0, is the intercept, β_1, β_2, β_3 are the corresponding coefficients and ε is an error term

The dependent variable is the inflow of CRT's and the independent variables are Gross Domestic product (GDP), Population (Pop), and the Time (T) variable is used as a proxy for the combined influence of the other variables on the inflow trend. The analysis period is from 1988 to 2000.

Step 1: Establish correlation between the inflow curve and the parameters

Table 5.7: results of the analysis of the individual factors on the inflow of CRT's

Estimation	Variables	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	β_3 (t-value)	R^2	R^2adj	F- statistics
1**	GDP	47.4 (1.1)	0.01 (3.186)			0.48	0.43	10.151
2**	Pop	2521 (-4.52)		7.3 (4.846)		0.68	0.65	23.490
3**	T	111.76 (8.498)			9.97 (6.01)	0.76	0.74	36.237

* significant at 95%
** significant at 99%

Table 5.7 shows the result of the relation between the inflow and GDP, Population and the time (T). Estimations 1 and 2 show a positive correlation between the GDP and the population as independent variables and the inflow as dependent variable with a fairly high coefficient of determination (R^2). Estimation 3 shows a positive correlation between the inflow and the time variable with a relatively higher (R^2). The correlation between the inflow of CRT's and all of the three variables is significant. The results indicate that the time variable and as a consequences the factors included in this variable (technological developments and substitution and maybe others) are important factors in the determination of the inflow shape. The results show also that the coefficient β_3 has a positive value which means the inflow will always increase with the time. This indicate that in the past the substitution does not have any influence on the inflow shape.

Step 2: Establish the relative importance of the parameters

Table 5.8: results of the analysis of the combined factors on the inflow of CRT's

Estimation	Variables	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	β_3 (t-value)	R^2	R^2adj	F- statistics
4**	GDP, Pop	-3351	-.008	9.7		0.69	0.63	11.517
		(-2.6411)	(-0.7317)	(2.679)				
5**	GDP,T	133.5	-0.0047		11.6	0.77	0.73	17.279
		(3.513)	(-0.613)		(3.629)			
6**	Pop, T	4811		-13	26.5	0.82	0.78	23.465
		(1.847)		(-1.804)	(2.855)			
7**	GDP, Pop, T	9225	0.015	-25.42	37.1	0.85	0.8	17.384
		(2.205)	(1.3196)	(-2.173)	(3.084)			

* significant at 95%
** significant at 99%

It is clear from the estimations 4,5,6 that the combination between two independent variables is improving the overall correlation goodness. It is also clear that the most important combination is when the time variable is included. When all the independent variable are included in the regression equation (estimation 7), R^2 has the highest value which prove the fact that all the three variable are significant.

Step 3: Establish the relation between the important influential aspects and the inflow curve

The best regression model as a result from the analysis is when the three independent variables the GDP, Population and the time are included in the model. The following model will be used to calculate the inflow of CRT's.

$$Inflow(t) = 9225 + 0.015\, GDP(t) - 25.42\, Pop(t) + 37.1\, T(t) \qquad (5)$$

Figure 5.6 shows the difference between the measured values of the inflow of CRT's and the calculated value from the regression model in equation 2

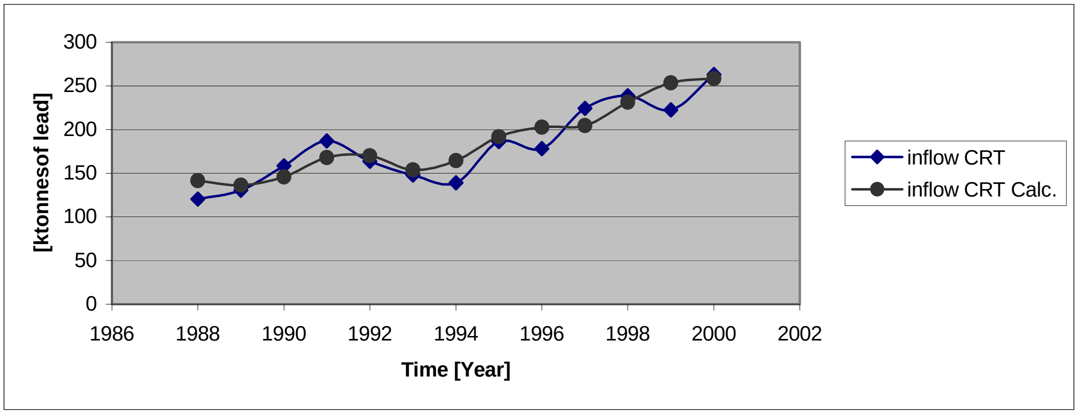


Figure 5.6: The difference between the measured and the calculated CRT's inflow

Modelling the outflow stocks

The outflow will be mainly determined by the discarding of CRT's, TV's and monitors. The life span of CRT's in the economic system is assumed to be 15 years. The outflow will be calculated according to equation 6. The results are shown in figure 5.7.

$$O(t) = I\,(t-L) \qquad (6)$$

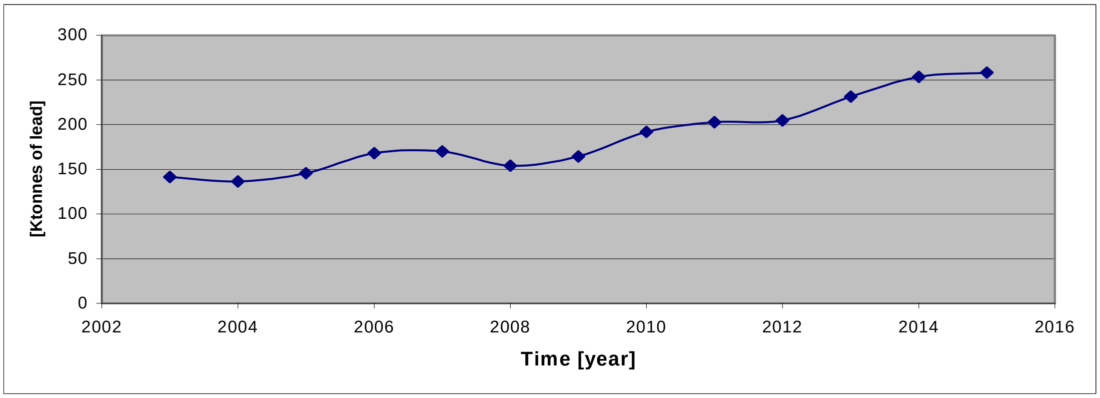


Figure 5.7: The outflow of CRT's

Modeling the outflow of product stocks using different life span distribution

The outflow out of the stocks depend on the mechanisms of delay and leaching. Delay is determined by the life span of the products: the outflow is determined by the past inflow, delayed by the life span of the application (equation 7). To obtain an accurate picture of stock formation and depletion, the distribution of the life span should be known (Kleijn et al., 2000). The empirical data on the life span is often not available. An alternative is to assume either an average life span or a certain life span distribution. Possible types of distribution are normal distribution, and skewed (Weibull) distribution.

$$F^{out}(t) = F^{in}(t - L) \qquad (7)$$

In this study, three alternatives of modelling the life span namely, the average life span, normal distribution and Weibull distribution of the life span will be examined using the case of lead in CRT's in the EU.

An average life span

The first and the easiest way is to assume an average life span of the concern application. The results for CRT's assuming an average life span of 15 year is depicted in figure 5.8.

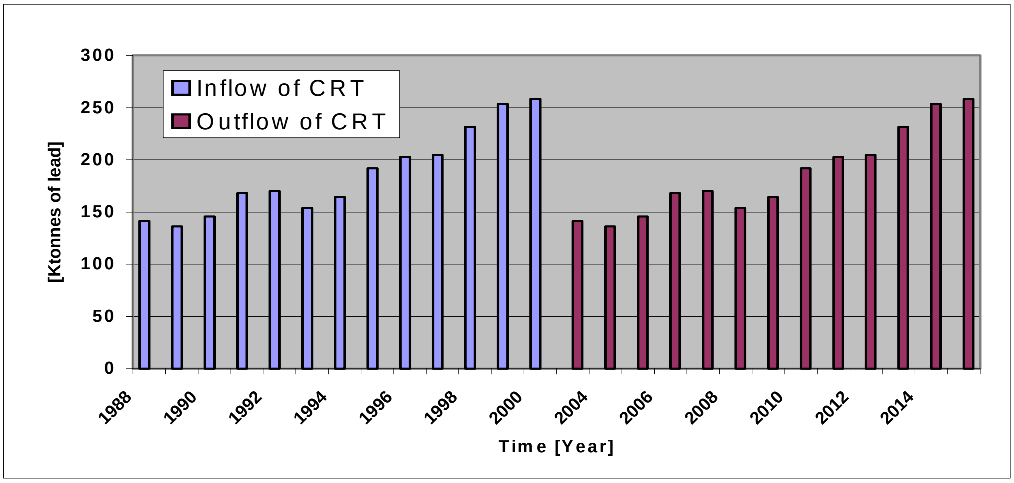


Figure 5.8: The inflow and the outflow of CRT's

Normal distribution of the life span

A normal distribution variable is characterised by a location parameter μ and a scale parameter σ. In the normal distribution, these two parameters are the mean and standard deviation of the distribution.

The distribution will be placed between two points representing a possible minimum (a) and maximum (b) values of the life span. From the interval [a, b], the location parameter and the scale parameter can be calculated. The values of these two parameter are given by equation 8 and 9.

$$\mu = (a + b) / 2 \qquad (8)$$

$$\sigma = (b-a) / 6 \qquad (9)$$

Probability density function (p.d.f.) of the normal distribution is given by equation 10.

$$P_t = \int_{t}^{t+1} f(x)\,dx \qquad (10)$$

in which $f(x)$ is given by equation 11:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\{-(x-\mu)^2 / 2\sigma^2\} \qquad (11)$$

For the cathode ray tubes (CRT's) in the computer monitors and televisions, a minimum value of the life span is assumed to be 12 year and a maximum value of 18 year. Figure 5.9 shows the outflow of the discarded CRT's based on the normal distribution of the life span for the produced CRT's in 1988.

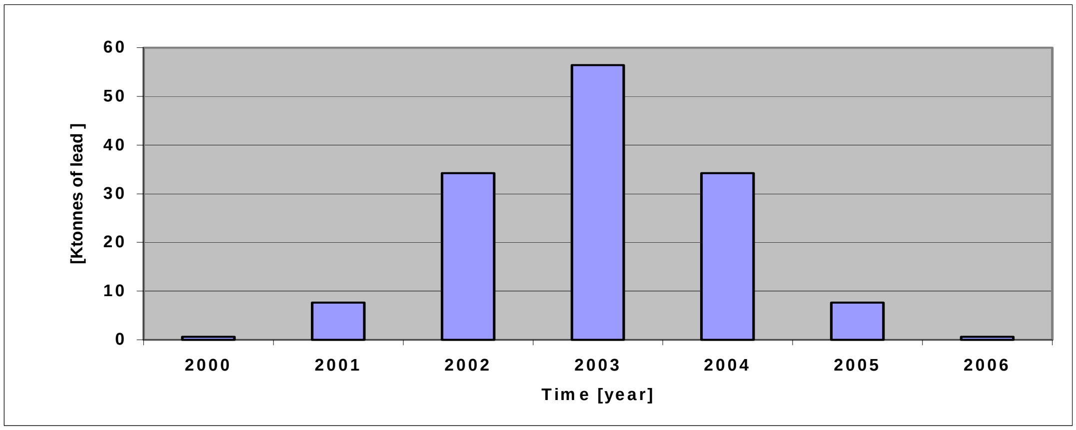


Figure 5.9: The outflow of the discarded CRT's produced in 1988

Weibull distribution of the life span

A Weibull random variable is characterised by a location parameter a, a scale parameter α and a shape parameter β. The probability density function (p.d.f.) is given by equation 12.

$$P_t = \exp\{-((t-a)/\beta)^{\alpha}\} - \exp\{-((t+1-a)/\beta)^{\alpha}\} \qquad (12)$$

The parameter α and β can be determined from the following equations

$$\alpha + \beta\,((\alpha - 1)/\alpha)^{(1/\alpha)} = m \qquad (13)$$

$$\alpha \ln[(b-a)/(m-a)] + \ln[(\alpha-1)/\alpha] - \theta = 0 \qquad (14)$$

with m a modal value and interpreted as the most likely value to be observed,
a and b the minimum and maximum values of the life span,

$\gamma = 0.997$,
$\theta = \ln \ln (1 / (1- \gamma))$.

For the cathode ray tubes (CRT's) in the computer monitors and televisions, a minimum value of the life span is assumed to be 12 year and a maximum value of 18 year. The modal value (m), the most likely life span, is assumed to be 15 years. Figure 5.10 shows the outflow of the discarded CRT's based on a Weibull distribution of the life span for the produced CRT's in 2000.

Figure 5.11 shows the results of the discarded CRT's in the period between 2000 and 2018 using both, the normal distribution and Weibull distribution of the life span.

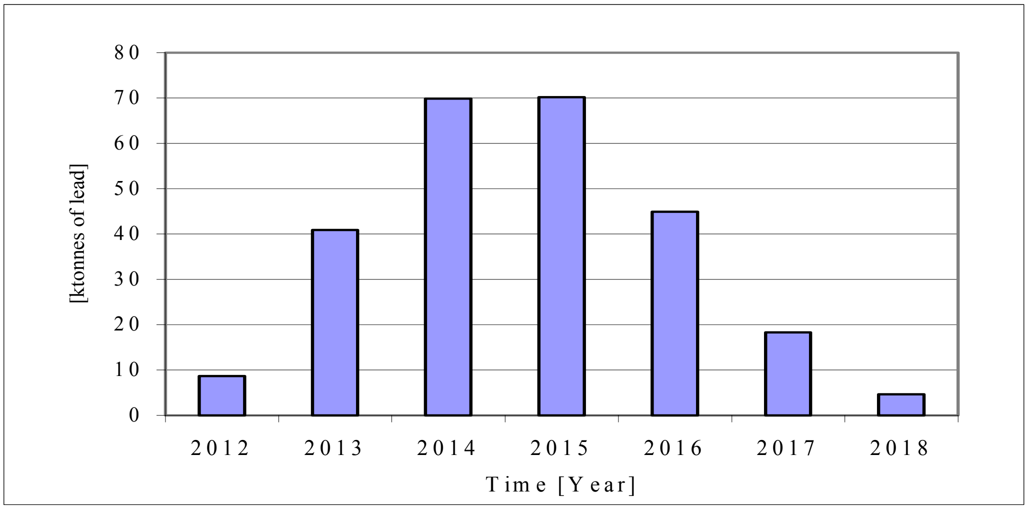


Figure 5.10: The outflow of the CRT's produced in 2000 based on Weibull distribution

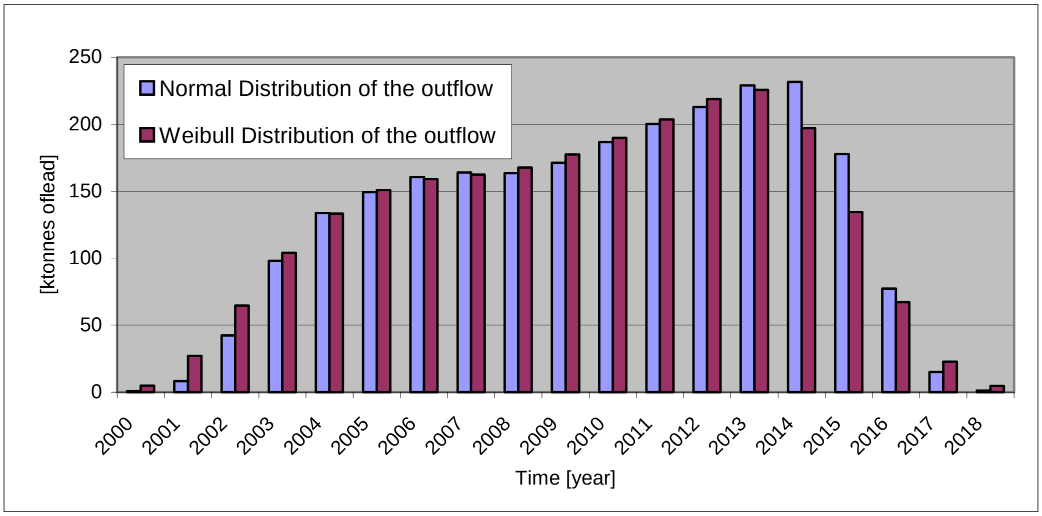


Figure 5.11: The discarded CRT's in the period between 2000 and 2018

As can be seen from figure 5.11, the results from the normal and Weibull distribution do not differ very much. This is mainly due to the assumption of the Weibull distribution parameters, however, the difference will be clear if an other value of the most likely life span has been chosen.

Modelling the outflow from a leaching process

Application is not possible in case of cathode ray tubes, since it is assumed that leaching of lead out of these applications does not take place.

Modeling the future inflow and outflow

The future inflow of CRT's can be calculated using the regression model combined with a projected values of the independent variables such as GDP and population. Long term projected values of the GDP and the population using different scenarios can be found in the literature (RIVM, 2001). In the CRT case, the future inflow has been calculated based on the Base Line scenario from 2000 through 2030. The future discarding of the CRT's from 2000 through 2042 can be modelled using the past inflow and the calculated future inflow and distributed life span. Figure 5.12 shows the future inflow and the future outflow, the life span is modelled as Weibull distribution.

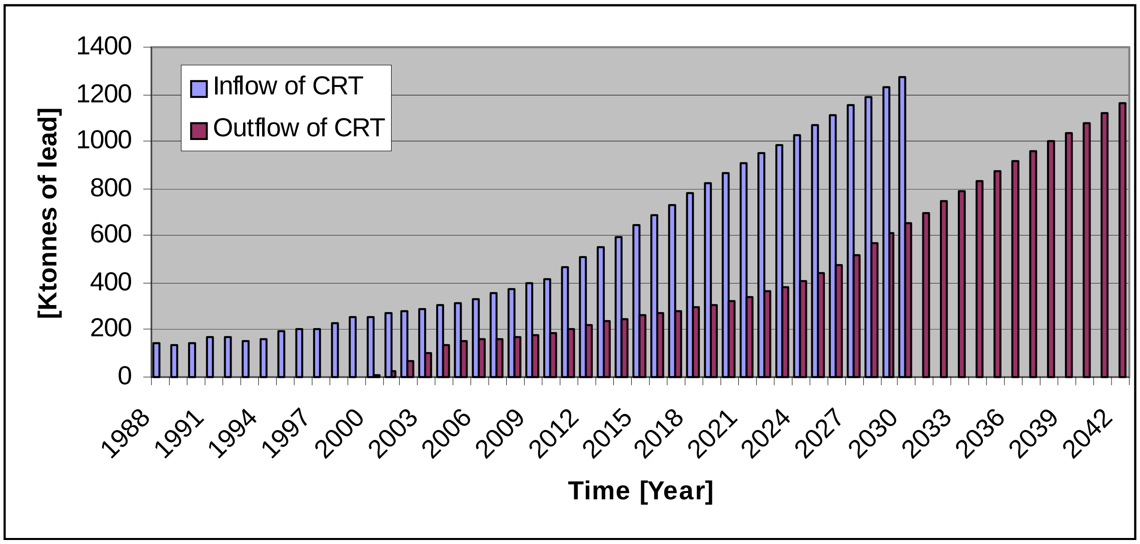


Figure 5.12: The future inflow and outflow of CRT's

6 CASE STUDY - LEAD IN THE DUTCH ECONOMY

6.1 General description of lead applications

Lead has been used in several applications due to its unique properties (corrosion resistance, conductivity, density and flexibility). The largest application is its use in batteries, the second largest application is lead sheet in buildings, and the third largest application is cathode ray tubes as applied in televisions and computer monitors. Cable sheathing used to be a large application in the past, however, the use of lead in cable sheathings is phased out.

Lead sheet has been used as flashing, weathering, roofing and cladding in the building industry due to its flexibility, high corrosion resistance, long lasting and attractive appearance.

Lead in batteries is applied in several applications such as industrial, traction and starting and lighting and ignition batteries (SLI). Industrial batteries are used as standby and storage batteries to provide emergency electricity in the event of power failure. Traction or stationary batteries are used where power is needed for a longer period of time in several applications such as forklifts, golf carts, floor sweepers and mining vehicles. SLI batteries are used in all vehicles with a combustion engine as the energy storage system for starting, lighting, and ignition. The automotive batteries are operating on the basis of the lead-acid/lead-oxide electrochemical system. Lead content of typical traction, industrial or SLI battery is about 58% of its weight.

Cable sheathing has been used in several applications such as indoor electricity in buildings and for outdoor electricity, telephones, and gas pipes.

Cathode ray tubes as applied in televisions and computer monitors are used as protection from harmful rays. The glass in cathode ray tube containing about 2 kg of lead in the form of lead silicate.

Small vehicles applications refer to small products normally are used in vehicles such as electronics, weight wheels, glazes, light bulbs, and bronze bushings and bearings. Wheel balancing weights are applied to wheel rims to compensate for static and dynamic unbalances and guarantee therewith true running of the tyres. Until today these weights are made of lead in most cases. The amount of lead used for wheel balancing lie between 20 and 25 g as an average. As each car is equipped with 10 weights, this sums up to 200-250 g lead per car. In this study an average of 225 g has been used. Light bulbs made of leaded glass are applied in interior and signal vehicle lamps. Additionally these lamps contain solder with a lead content. Lamps in cars contain between 0.2 to 0.75 g lead in the glass bulb and solder contributes up to 0.2 g lead per lamp. As an average value 0.4-0.5 g lead per bulb is stated. An average car is equipped with 30 to 40 lamps, this sums up to 12 g lead per vehicle. This value has been used in this study. Electronics, glazes, and bronze bearings and bushings have been used in the vehicles industry for different purposes. Electronics in cars contain about 52.7 g. Glazes in cars contain about 1.2 g. Bronze bearings and bushings in cars contain about 10 g (IEPA, 2001).

Substitution

As a substitute for lead in roofing, many alternatives exist including lead-clad sheet and galvanized (zinc coated) steel sheet. Zinc and copper are traditionally used in some countries and have advantages similar to lead for these purposes. Many non-metallic materials are in common use as well, but these materials require more maintenance and have a much shorter lifetime than lead. For leaded window frames, no viable alternatives exist at present. However, for lead /acid batteries, no viable substitution exists at present. The advent of modern materials such as plastic and aluminium has reduced the need for lead on many types of power cables but for the protection of the very high voltage cables which enable electricity to be transmitted over long distance under water, there is no alternatives to lead. For cathode ray tubes, Lead additions give excellent shielding properties to glass. No viable alternatives are known of at present. Some researcher indicates that it could be possible to replace the lead with other materials such as barium, strontium, and zirconium but no such a glass is commercially available and it is not known if these materials can be supplied in sufficient quantities to meet demand. The lead demand for cathode ray tubes reflects the increase in demand for television and computer terminals. It is likely that the use of cathode ray tubes will decline as a result of the advent of flat screen displays. It is very hard to predict how fast such displays will totally remove cathode ray tubes from the market.

Life span, emissions and recycling rate

The main model parameters are the lead containing products life span, emission factor and waste stream distribution. The most likely life span, emission factor and waste stream distribution of the different lead applications (table 6.1) can be found in different studies (Tukker, 2001 and Palm, 2000). The minimum and maximum life span (table 6.1) are our own assumption.

Table 6.1: Life span, emission factors and waste stream rates of lead applications

Application	Emission factor %	Minimum life span (year)	Maximum life span (year)	Most likely life span (year)*	Recycling (%)*	Landfill (%)*	Incineration (%)*
Lead sheet	0.008*	45	75	50	90	8	2
Batteries							
Industrial	0	3	12	10	100	0	0
Traction	0	3	8	5	95	3.5	1.5
SLI	0	4	8	5	95	3.5	1.5
Cable sheathing							
Indoor	0.008*	20	45	30	75	0	0
Outdoor	0.025**	20	45	30	75	0	0
Cathode ray tubes							
Televisions	0	10	25	15	50	40	10
Computers	0	10	25	15	50	40	10
Small vehicle Applications	0	2	20	12	0	75	25

* Tukker, 2001 ** Palm, 2002

The effect of the initial stock

The outflow of lead from the stock of products-in-use is the amount of discarded lead and the emissions during use. The discarded outflow is estimated as a delayed inflow and the emission during use as a fraction of the stock. In some applications such as lead sheet, cable sheathing and cathode ray tubes, the future outflow will be affected by the initial stock (the stock generated before the available statistical figures of the inflow). Therefore, we estimated an initial stock for those applications and assumed that this stock will be completely discarded and emitted in a period that is equal to the most likely life span. Ultimately, the outflow in a certain period is the summation of the outflow due to the initial stock and the outflow due to the known past inflow.

6.2 Lead sheet in buildings

6.2.1 The inflow of lead sheets in buildings

The inflow of lead sheets into the stock of the products-in-use of the Dutch economy from 1988 till 1999 is the amount of lead sheets produced inside the system mainly from secondary material plus the imported amount of lead sheets minus the exported amount. Lead sheets are used in two different applications in the building industry; houses and utility building. We have no information on the division of the lead over the two categories "houses" and "utility buildings". We assume that half the amount of lead sheets is used for houses, the other half going to utility buildings. To calculate the average amount of lead in each house, two steps are taken: (1) the total inflow of lead sheets is divided by 2 to calculate the amount of lead used by houses and (2) the thus estimated lead flow into the stock of houses is then divided by the number of the newly constructed houses. The average amount of lead in houses in the Netherlands thus calculated is 146.95 kg/house. Table 6.2 shows the total inflow of lead sheets in buildings and the inflow of lead sheets in housing sector.

Table 6.2: Lead sheet inflow in buildings and housing sector (tonnes) (ILZSG,1999)[a] (CBS,2000)

year	Lead sheets in buildings	Lead sheets in houses
1988	29075	14537
1989	30190	15095
1990	28845	14422
1991	25909	12954
1992	27346	13673
1993	27735	13867
1994	28006	14003
1995	26764	13382
1996	28875	14437
1997	24517	12258
1998	24241	12120
1999	32831	16415

a- ILSZG (1999) gives production data for all extruded products. Lead sheet in the NL is about 98.5% of this volume.

Due to the long life span of lead sheets in buildings, the past inflow is needed. The past inflow of lead sheets in houses is calculated from the past figures of the new built houses and the average amount of lead in each house. The calculated inflow is multiplied by 2 to correct for the utility building. The past inflow of lead sheets starting from 1950 is shown in figure 6.1.

6.2.2 Stock of lead sheets in 1950

The stock of lead sheets in buildings in 1950 is calculated from the total number of houses in 1950 and the average amount of lead sheets in each house. The calculated stock is multiplied by 2 to correct for the utility buildings. In the Netherlands, the stock of lead sheets in buildings in 1950 was 639526 tonnes.

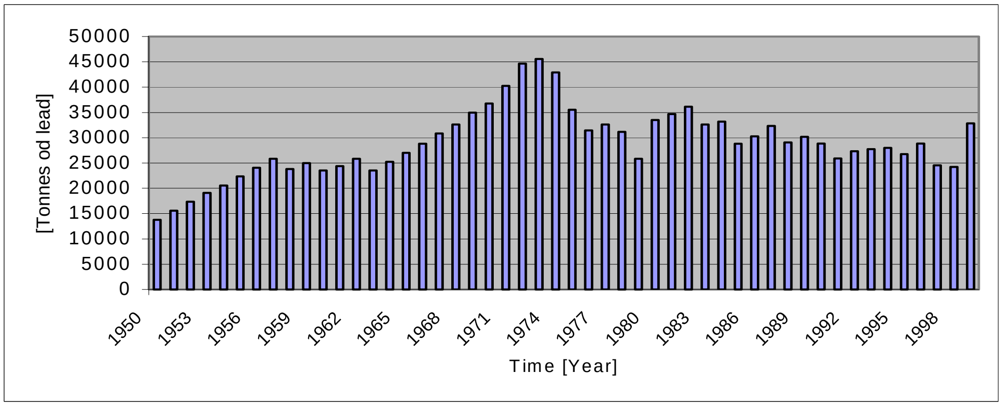


Figure 6.1: Past inflow of lead sheets in buildings

6.2.3 Outflow of lead sheets

The outflow of lead sheets from the stock is the amount of the discarded lead sheets either with the demolished houses or due to renewing and replacement and the emission during use. Due to statistical reasons, and the long life span of the lead sheets, the outflow of lead sheets is calculated in two different periods.

First, the stock of lead sheets in 1950 is discarded (demolished houses and replacements) in 50 years starting in 1950 and ending in 1999 and as emissions in the same period.

$$F^{out}disc(t) = \alpha * S(1950) \tag{1}$$

$$F^{out}em\ (t) = \gamma * S(t) \tag{2}$$

$$\alpha = 1/50 = 0.02 \tag{3}$$

$$\gamma = 0.008\%$$

Second, the outflow due to discarded lead sheets (demolished houses and replacements) from 1996 onwards is calculated based on the inflow of lead sheets from 1950 till 1999 and a Weibull distribution of the life span. The minimum life span is 45 years, the maximum is 75 and the most likely life span is 50 years. The outflow due to the emissions of lead sheets is calculated as a fraction of the stock.

$$F^{out}disc(t) = F^{in}\ (t-L) \tag{4}$$

$$F^{out}em\ (t) = \gamma * S(t) \tag{5}$$

The stock of lead sheets in buildings is calculated based on equation 6.

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

6.2.4 Waste treatment of lead sheets

The outflow of discarded lead sheets from the stock will be partly recycled and partly will end up in the final waste treatment either in the landfill sites or the incineration plants. The recycling percentage of lead sheets is 90% of the discarded stream. The stream of final waste is split between landfill 8% and incineration 2%. The results are shown in figure 6.3.

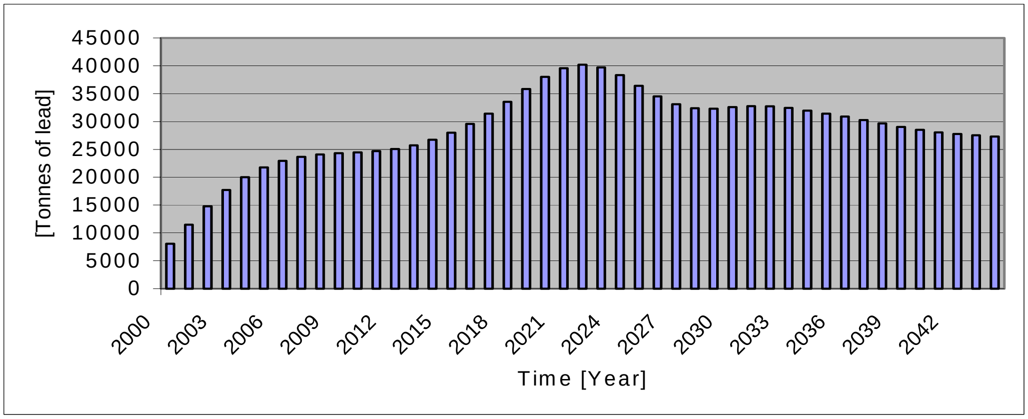


Figure 6.2: Discarded lead sheets

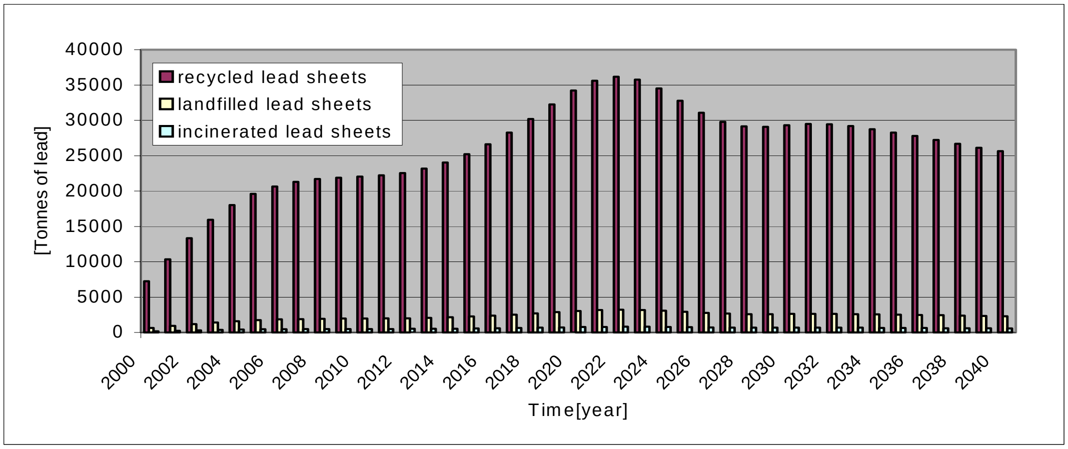


Figure 6.3: Waste treatment of lead sheets in buildings

6.2.5 A model equation of the inflow of lead sheet

The inflow of lead sheet has been tested with the different factors such as the GDP, per capita GDP , population size and the time variable. The results of the analysis are shown appendix B. The results show a positive and significant correlation between the inflow and the population growth with a time delay of 14 years. The combined price of one year and three years time delay has a significant correlation with the inflow and the coefficient associated with the price has the expected negative sign. The results also show that when both the population growth and the price are combined in one model, both turned out to be insignificant. In this case both the price and the population growth separately can be used to predict the future inflow of lead sheet, however, the model with the population growth will be used because the future developments in the population can be more reliable than the price. The following model will be used to calculate the inflow:

$$Inflow = 21583 + 65064*PopG\ (t-14) \qquad (7)$$

Using equation 7, the inflow of lead sheets has been calculated and compared with the one quantified from the statistics. Figure 6.4 shows the results.

6.2.6 Future inflow of lead sheets

The future inflow of lead sheets has been calculated based on equation 7 and the real values of the population growth. Figure 6.5 shows the results.

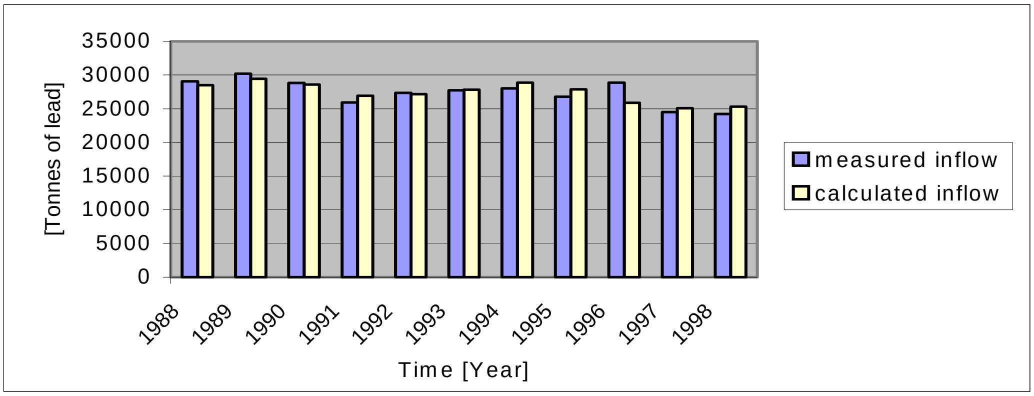


Figure 6.4: Measured and calculated inflow of lead sheets in buildings

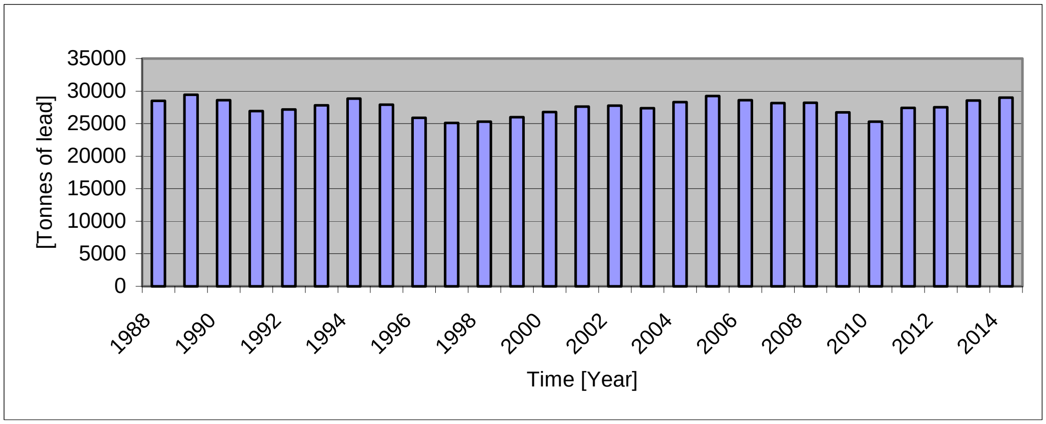


Figure 6.5: Past and future inflow of lead sheets

6.2.7 Future outflow of lead sheets

The outflow of lead sheets from the stock of products-in-use phase is the amount of the discarded lead sheets either with the demolished houses or due to renewing and replacement and the emission during use. The future discarded lead sheets (demolished houses and replacements) is calculated based on the past and future inflow of lead sheets and a Weibull distribution of the life span. The results are shown in figure 6.6. The outflow due to the emissions of lead sheets is calculated as a fraction of the stock and the results are shown in figure 6.7.

6.2.8 Future waste treatment of lead sheets

The outflow from the products-in-use stock will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of lead sheets is 90% of the discarded stream. The stream of final waste is split between landfill 8% and incineration 2%. The results are shown in figure 6.8.

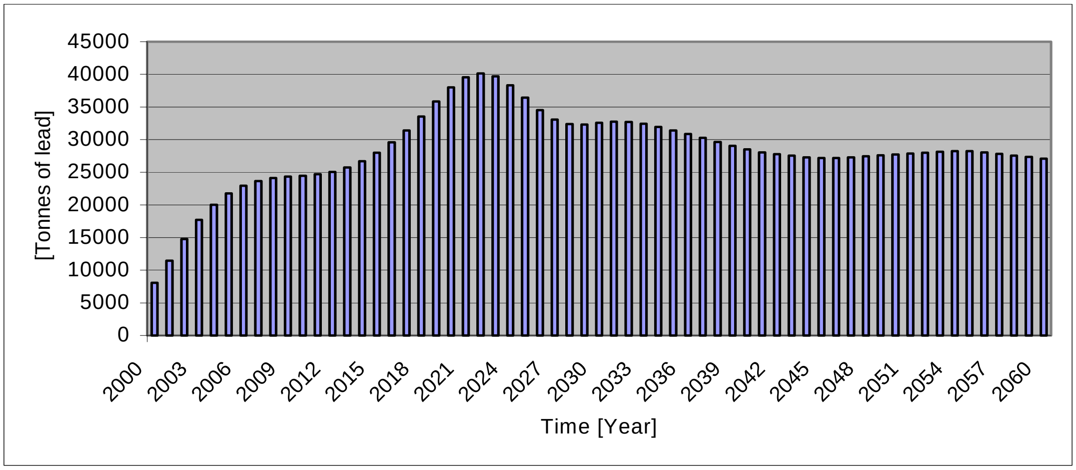


Figure 6.6: Future discarded lead sheets

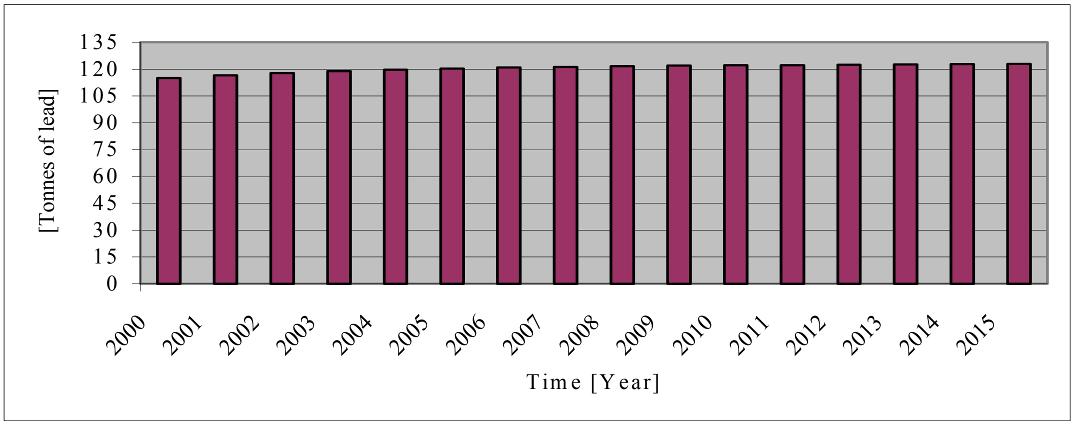


Figure 6.7: Future emissions of lead sheets

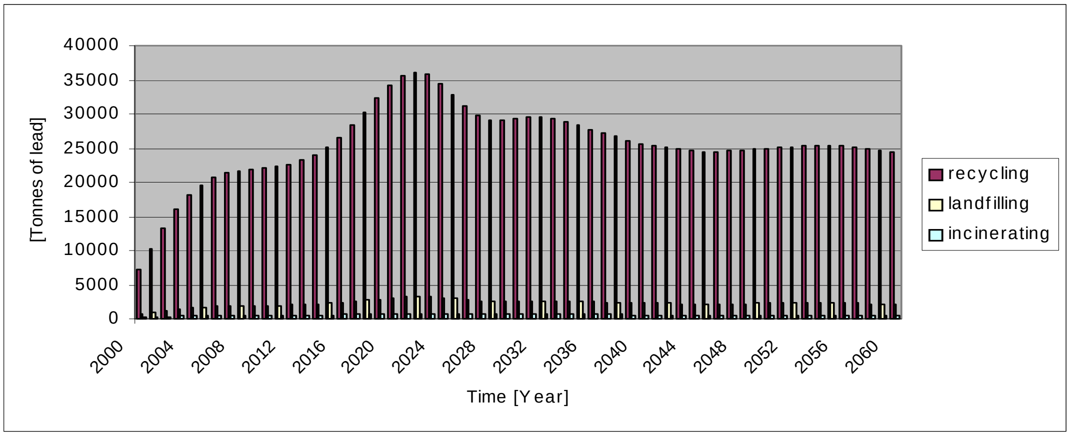


Figure 6.8: Waste treatment of lead sheets

6.3 Batteries

6.3.1 Industrial batteries

6.3.1.1 The inflow of industrial batteries

The inflow of industrial batteries into the stock of the products-in-use of the Dutch economy is the amount of industrial batteries produced inside the system plus the imported amount of industrial batteries minus the exported amount. Figure 6.9 shows the inflow of the industrial batteries in the period 1988-1999 (ILZSG, 1999), (CBS, 2000).

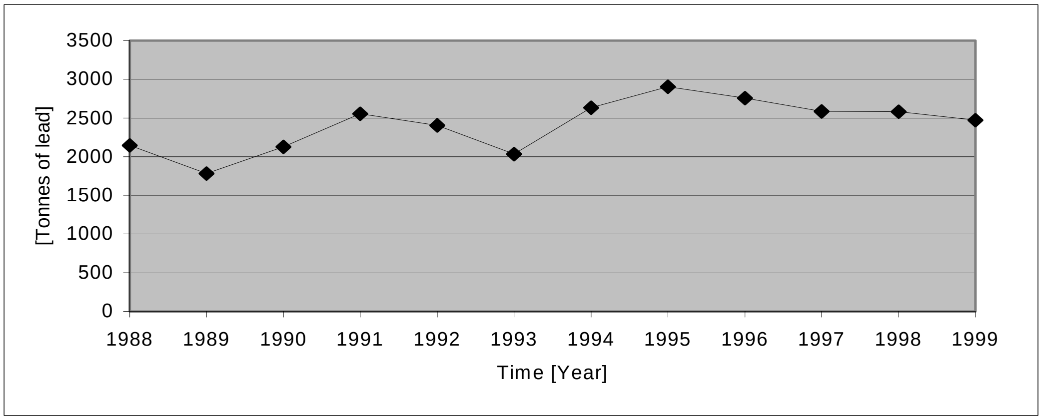


Figure 6.9: The inflow of industrial batteries

6.3.1.2 A model equation for the inflow of the industrial batteries

The inflow of the industrial batteries has been tested with the different factors such as the GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B.

The results indicate a positive correlation between the GDP, per capita GDP, population, and time variable and the inflow of industrial batteries. The correlation between the inflow of industrial batteries and population and time is significant at 95% probability level. The correlation between the inflow and GDP and per capita GDP is significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is fairly high. When variables such as per capita GDP and population or per capita GDP and time were combined, the population and time variables are losing their significant and the coefficient of determination has not changed significantly from the one associated with the per capita GDP without additional variables. The results indicate that the factors included in T (technological developments and substitution and maybe others) are not important factors in the determination of the inflow shape. Therefore, the following model will be used to calculate the inflow of the industrial batteries:

Inflow = 783 + (7.62*GDP/capita) (8)

Using equation 8, the inflow of industrial batteries has been calculated and compared with the one calculated from the statistics. Figure 6.10 shows the results.

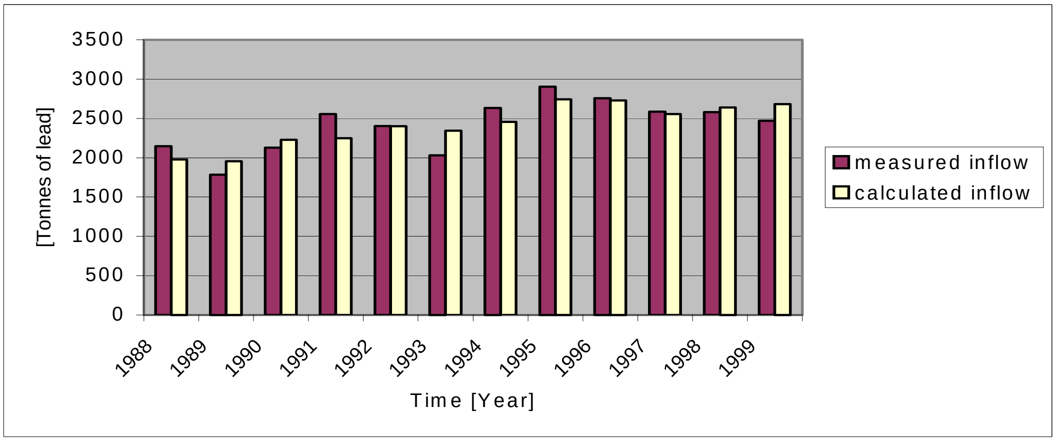


Figure 6.10: Measured and calculated inflow of the industrial batteries

6.3.1.3 Future inflow of the industrial batteries

The future inflow of the industrial batteries has been calculated based on equation 8 and scenario projections of the per capita GDP.

6.3.1.4 Future outflow of the industrial batteries

The outflow of industrial batteries from the stock of the products-in-use is the amount of the discarded industrial batteries. No emission occurs during the use of industrial batteries. The future discarding of industrial batteries is calculated based on the future inflow and a Weibull distribution of the life span. The minimum life span is 3 years, the maximum is 12 years and the most likely life span is 10 years.

Figure 6.11 shows the past and future inflow and discarded outflow of industrial batteries.

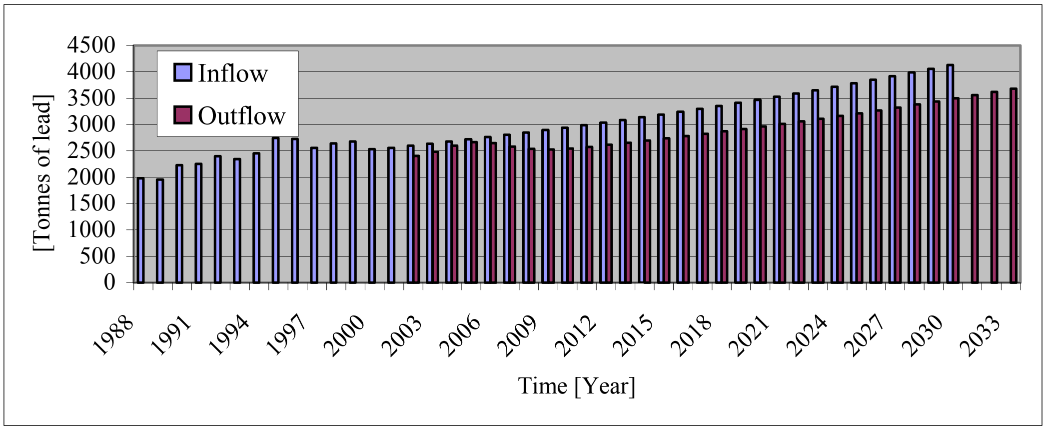


Figure 6.11: Past and future inflow and discarded outflow of industrial batteries

6.3.1.5 *Waste treatment of the industrial batteries*

Industrial battery lead has a recycling rate of almost 100 percent. The lead is melted, poured into ingots and used to produce new batteries. The polypropylene cases are broken apart, washed, melted, and extruded into pellets, which are used to make new battery cases. The spent battery acid is processed to extract components that are converted to sodium sulphate, a product used in textiles, detergents and other products.

6.3.2 Traction batteries

6.3.2.1 *The inflow of traction batteries*

The inflow of traction batteries into the stock of products-in-use of the Dutch economy is the amount of traction batteries produced inside the system plus the imported amount of traction batteries minus the exported amount. Traction batteries enters the economy either as a separate product or in combination with other products such golf carts and others. When the inflow of traction batteries to be calculated, the amount of batteries corresponding to the amount of these products should be included. Figure 6.12, shows the inflow of the traction batteries in the period 1988-1999 (ILZSG, 1999), (CBS, 2000).

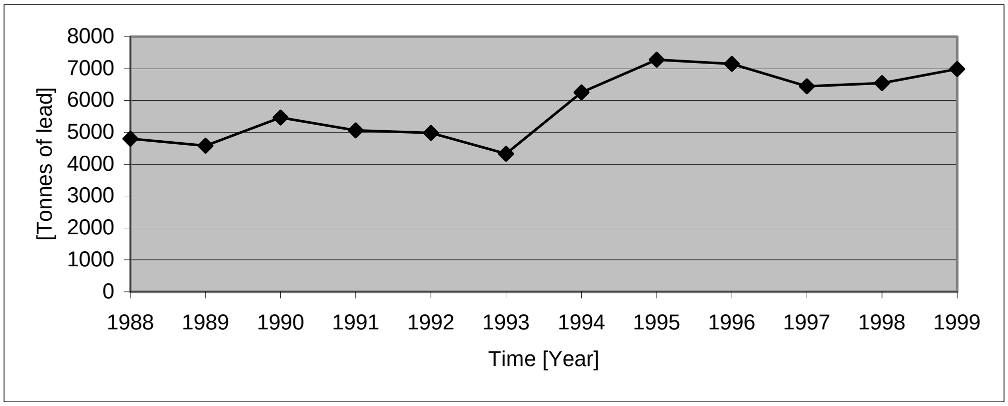


Figure 6.12: The inflow of traction batteries

6.3.2.2 *A model equation for the inflow of the traction batteries*

The inflow of traction batteries has been tested with the different factors such as GDP, per capita GDP, population size and the time variable to evaluate the most important determinants of the inflow shape. The results of the analysis are shown in appendix B.
The results indicate a positive correlation between the GDP, per capita GDP, population, and time variable and the inflow of traction batteries. The correlation between the inflow of traction batteries and all variables is significant at the 99% probability level. The coefficient of determination (R^2) associated with the correlation is high. When variables such as per capita GDP and population or per capita GDP and time were combined, the population and time variables are losing their significant and the coefficient of determination has not changed from the one associated with the per capita GDP without

additional variables. Therefore, the following model will be used to calculate the inflow of the traction batteries:

$$Inflow = 236.45 + (26.1 * GDP/capita) \qquad (9)$$

Using equation 9, the inflow of industrial batteries has been calculated and compared with the one calculated from the statistics. Figure 6.13 shows the results.

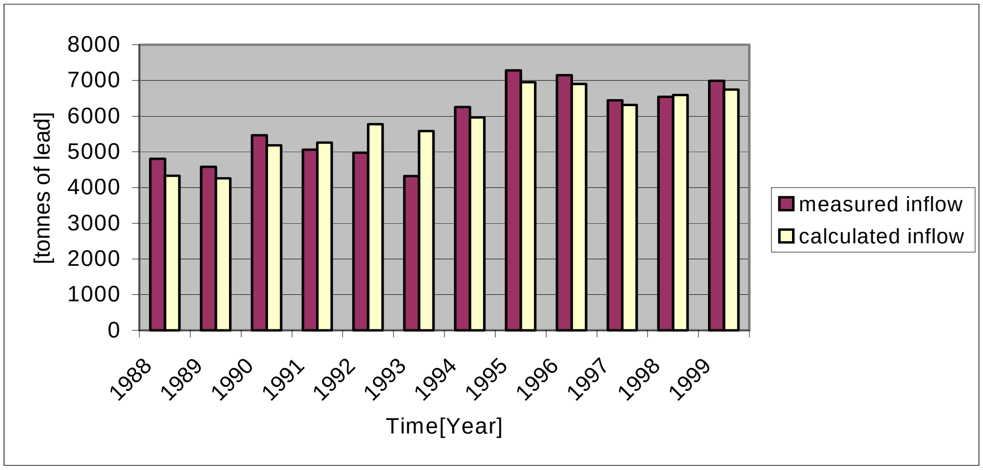


Figure 6.13: Measured and calculated inflow of traction batteries

6.3.2.3 Future inflow of traction batteries

The future inflow of the traction batteries has been calculated based on equation 1 and scenario projections of the per capita GDP.

6.3.2.4 Future outflow of traction batteries

The outflow of traction batteries from the stock of products-in-use is the amount of the discarded traction batteries. No emission occurs during the use of traction batteries. The future discarding of traction batteries is calculated based on the future inflow and a Weibull distribution of the life span. The minimum life span is 3 years, the maximum is 8 years and the most likely life span is 5 years.

Figure 6.14 shows the past and future inflow and discarded outflow of traction batteries.

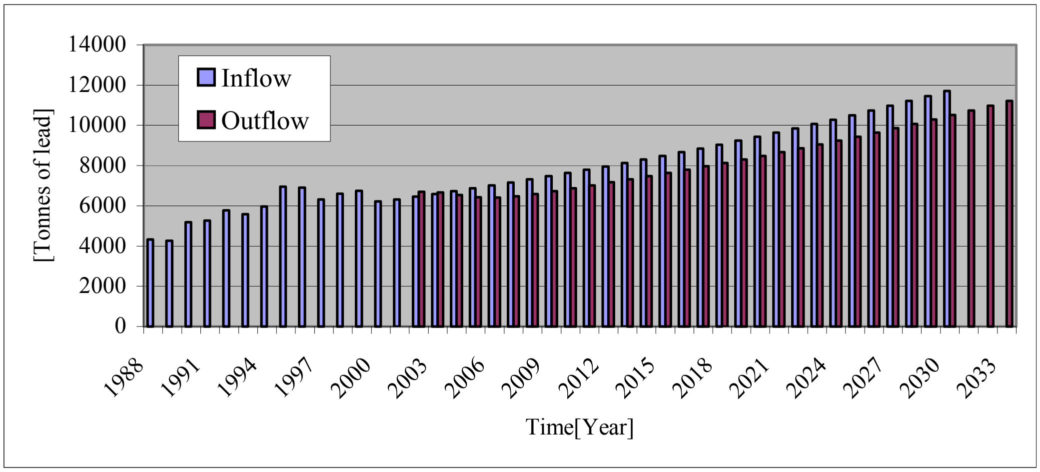


Figure 6.14: Past and future inflow and discarded outflow of traction batteries

6.3.2.5 Waste treatment of traction batteries

The outflow from the products-in-use stock will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of traction batteries is about 95% of the discarded batteries. The stream of final waste is split between landfill 3.5% and incineration 1.5%. The results are shown in figure 6.15.

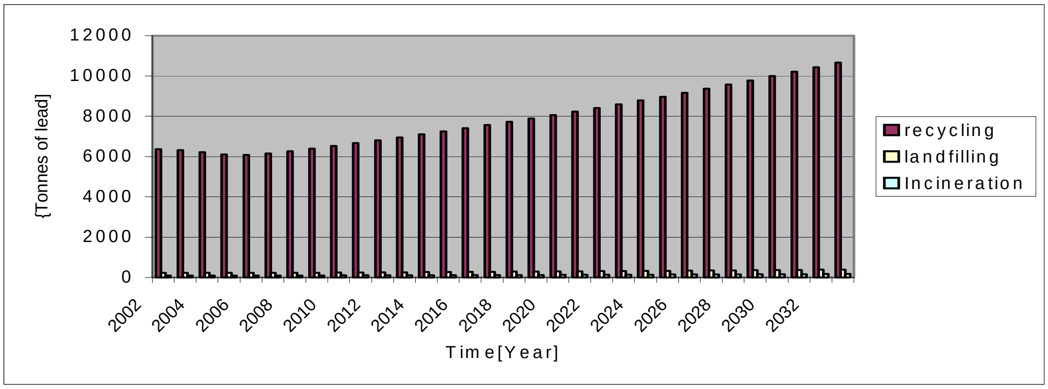


Figure 6.15: Recycled, landfilled, and incinerated streams of traction batteries

6.3.3 SLI batteries

6.3.3.1 The inflow of SLI batteries

The inflow of SLI batteries into the stock of the products-in-use of the Dutch economy is the amount of SLI batteries produced inside the system plus the imported amount of SLI batteries minus the exported amount. SLI batteries enter the economy either as a separate product or in combination with other products such as cars, lorries and trucks. When the inflow of SLI batteries to be calculated, the amount of batteries corresponding to the amount of these vehicles should be included. Figure 6.16 shows the inflow of SLI batteries in the period 1988-1999 (ILZSG, 1999), (CBS, 2000).

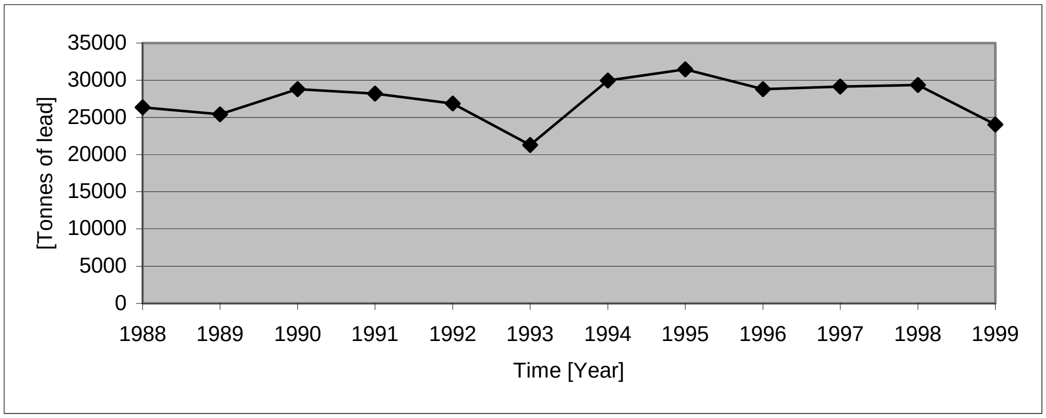


Figure 6.16: The inflow of SLI batteries

6.3.3.2 A model equation for the inflow of SLI batteries

The inflow of SLI batteries has been tested with the different factors such as the population, GDP and per capita GDP. The results of the analysis are shown in appendix B.

The results indicate a positive and negative correlation between the population with a time delay of different years and the inflow of SLI batteries. The correlation between the inflow of SLI batteries and the population growth with a time delay of 4,12, and 13 years is significant at the 95% probability level. The coefficient of determination (R^2) associated with the correlation is rather low. Although the correlations between the inflow and the population growth with a time delay of 12 and 13 years are significant, we do not choose to use these models to estimate the future inflow because β_1 associated with the correlation has an unexpected negative sign.

Moreover, the results indicate a positive correlation between the GDP with a time delay of different years and the inflow of SLI batteries. The correlation between the inflow of SLI batteries and the GDP is not significant and the coefficient of determination (R^2) associated with the correlation is very low. The results also indicate a positive correlation between the per capita GDP with a time delay of different years and the inflow of SLI batteries. The correlation between the inflow of SLI batteries and the per capita GDP is also not significant and the coefficient of determination (R^2) associated with the correlation is very low.

In general, the best correlation is the one with the population growth with a time delay of 4 years. Therefore, although the correlation is not significant, the following model will be used to calculate the inflow of the SLI batteries:

$$Inflow = 18756 + (95726 * popG\ 84) \qquad (10)$$

Using equation 10, the inflow of SLI batteries has been calculated and compared with the one calculated from the statistics. Figure 6.17 shows the results.

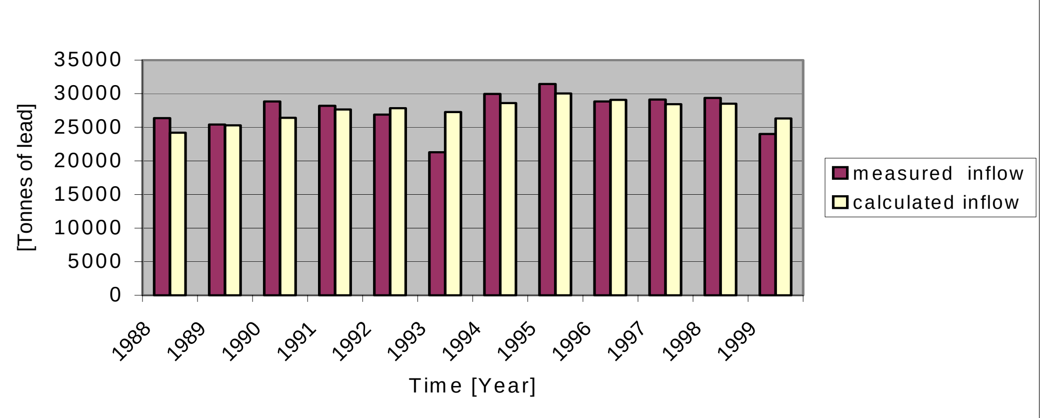


Figure 6.17: Measured and calculated inflow of SLI batteries

6.3.3.3 Future inflow of SLI batteries

The future inflow of SLI batteries has been calculated based on equation 3 and the real values of the population.

6.3.3.4 Future outflow of SLI batteries

The outflow of SLI batteries from the stock in the products-in-use is the amount of the discarded SLI batteries. No emission occurs during the use of SLI batteries. The future discarding of SLI batteries is calculated based on the future inflow and a Weibull distribution of the life span. The minimum life span is 4 years, the maximum is 8 years and the most likely value is 5 years.

Figure 6.18 shows the past and future inflow and discarded outflow of SLI batteries.

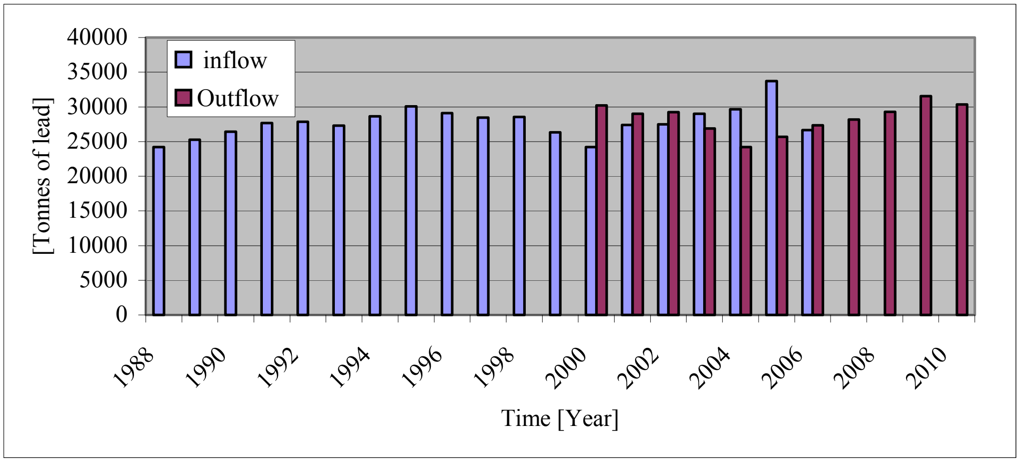


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Figure 6.18: Past and future inflow and discarded outflow of SLI batteries

6.3.3.5 Waste treatment of SLI batteries

The outflow from the products-in-use stock will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of SLI batteries is about 95% of the discarded batteries. The stream of final waste is split between landfill 3.5% and incineration 1.5%. The results are shown in figure 6.19.

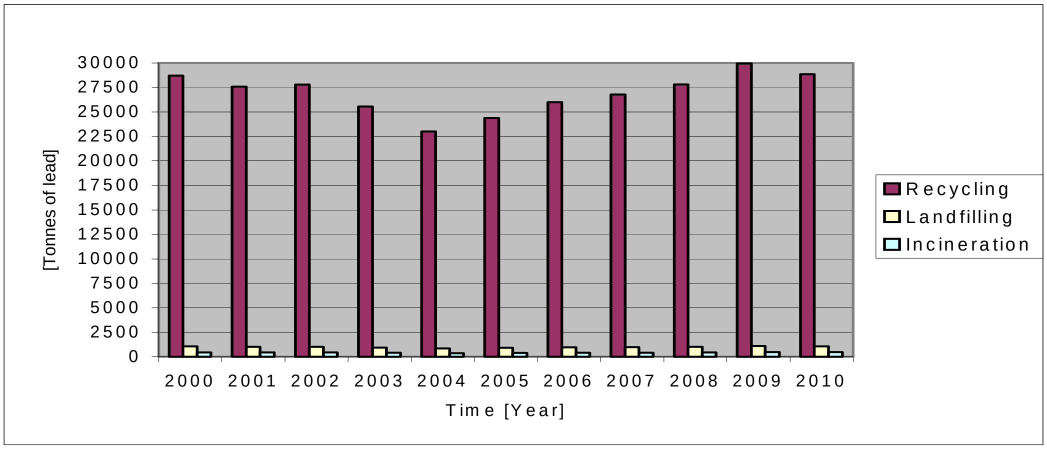

Figure 6.19: Recycled, landfilled, and incinerated streams of SLI batteries

6.4 Cable sheathing

6.4.1 Indoor cable sheathing (electricity building)

6.4.1.1 Inflow of indoor cable sheathing

The inflow of indoor cable sheathing into the products-in-use stock in the Dutch economy in the past has been measured based on the figures of construction of new houses and an assumption that the amount of lead in cable sheathing equals 1.5 kg/house (Palm, 2002). Lead in these applications has been phased out in 1970.

6.4.1.2 Stock of indoor cable sheathing

The stock of cable sheathing used for electricity cables in buildings in 1950 has been calculated based on the assumption that each building has 1.5 kg of lead due to the use of indoor cable sheathing and the stock of houses in the Netherlands in 1950. To correct for the utility buildings, the calculated value of the stock has been multiplied by 2. The stock of lead in cable sheathing in 1950 thus calculated was 6528 tonnes.

6.4.1.3 Outflow of indoor cable sheathing

The outflow of cable sheathing from the stock of products-in-use is the amount of the discarded cable sheathing (demolished houses and replacement of cables) plus the emissions during use. The outflow of cable sheathings is calculated in two different steps. First, the outflow due to the initial stock of 1950 and second, the outflow due to the delayed inflow.

Stock of cable sheathing in 1950 is discarded (demolished houses and replacements) in 30 years (the most likely life span) starting in 1950 and ending in 1980 and as emissions in the same period as given by equations 11-13.

$$F^{out}disc(t) = \alpha * S(1950) \qquad (11)$$

$$F^{out}em\ (t) = \gamma * S(t) \qquad (12)$$

$$\alpha = 1/30 \qquad (13)$$

$$\gamma = 0.008\%$$

The outflow due to discarded cable sheathing (demolished houses and replacements) from 1970 onward is calculated based on the inflow of cable sheathing from 1950 till 1980 and a Weibull distribution of the life span. The minimum life span is 20 years, the maximum is 45 and the most likely life span is 30 years. The outflow due to the emissions of is calculated as a fraction of the stock.

$$F^{out}disc(t) = F^{in}\ (t\text{-}L) \qquad (14)$$

$$F^{out}em\ (t) = \gamma * S(t) \qquad (15)$$

The stock of cable sheathing in buildings is calculated based on equation 6.

S(t+1) = S(t) + inflow (t) – Outflow (t) **(16)**

Figure 6.20 shows the results. The figure shows a gap in the discarded outflow between the year 1979 and 1980. This is due to the assumption on discarded outflow due to the initial stock of 1950, which ends in the year 1980.

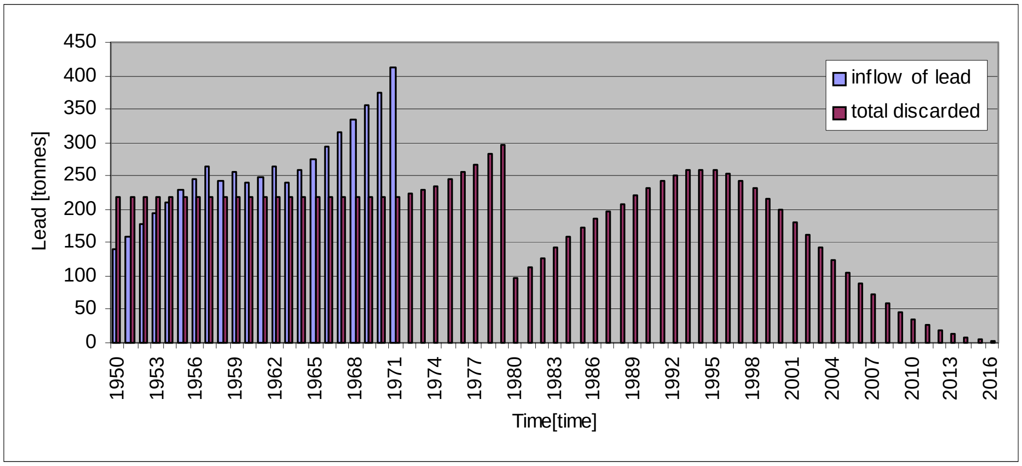

Figure 6.20: The inflow and outflow of indoor cable sheathing

6.4.2 Outdoor cable sheathing

6.4.2.1 Stock of outdoor cable sheathing (1960-1990)

The stock of outdoor cable sheathing (1960-1990) in the products-in-use of the Dutch economy in the past has been calculated based on the population figures and an assumption that the lead amount per capita due to the use of cable sheathing in outdoor electricity is 16.7 kg, in outdoor telephones is 12.84 kg, and in outdoor gas pipes is 0.173 kg (Palm, 2002). Lead in these applications is phased out since 1990.

Based on the above mentioned assumption, the stock of lead in outdoor cable sheathing was calculated to be 341313.231 tonnes in the year 1960.

The difference between the calculated stocks in two consecutive years is the net inflow to the consumption-and-use phase, which equals the inflow minus the outflow

Net inflow = S(t+1) – S(t) = Inflow(t) – Outflow(t) ***(17)***

6.4.2.2 Outflow of cable sheathing (1960-1980)

The outflow from 1960 to 1980 is calculated as the emissions during use plus the discarded amount of cable sheathing from the initial stock of 1960. The calculation of the outflow has been stopped at 1980 due to the possible affect of the inflow of 1960 through 1980, which ultimately will be calculated from the outflow in this period on the outflow of 1980 onwards.

$$\textit{Outflow}(t) = F^{out}\,\textit{discarded}(t) + F^{out}\,\textit{emission}(t) \tag{18}$$

$$F^{out}\textit{disc}(t) = \alpha * S(1960) \tag{19}$$
$$F^{out}\textit{em}(t) = \gamma * S(t) \tag{20}$$
$$\alpha = 1/30 \tag{21}$$
$$\gamma = 0.025\%$$

6.4.2.3 Inflow of cable sheathing

The inflow of cable sheathing is calculated in two different steps due to the minimum life span of cable sheathing (20 years) which will lead to a possible affect of the inflow on the outflow.

For the period from 1960 through 1980, the inflow of outdoor cable sheathing has been calculated from the stock and the outflow from 1960 through 1980 as given by equation 22 and 23.

$$S(t+1) = S(t) + \textit{inflow}(t) - \textit{Outflow}(t) \tag{22}$$
$$\textit{Inflow}(t) = S(t+1) - S(t) + \textit{Outflow}(t) \tag{23}$$

The calculation stopped at 1980 because the outflow after 1980 will be affected by the outflow from the distributed inflow of 1960.

From 1980 - 1990 the inflow of outdoor cable sheathing has been calculated from the stock and the outflow from 1980 –1990 as given by equation 23. The calculation of the outflow in this period will be described 6.7.2.4. The inflow from 1990 onwards is 0.

6.4.2.4 Outflow of cable sheathing

From 1980 –2035 the outflow of cable sheathing is the discarded cable sheathing and the emissions during use. The outflow due to discarded cable sheathings is calculated based on the inflow of cable sheathings from 1960 till 1980 and a Weibull distribution of the life span. The minimum life span is 20 years, the maximum is 45 and the most likely life span is 30 years. The outflow due to the emissions is calculated as a fraction of the stock.

6.4.2.5 Stock of cable sheathing (1990-2035)

$$S(t+1) = S(t) + \textit{inflow}(t) - \textit{Outflow}(t) \tag{24}$$

The results are shown in figure 6.21. The figure shows a gap in the discarded outflow between the year 1988 and 1990. This is due to the assumption on discarded outflow due to the initial stock of 1960.

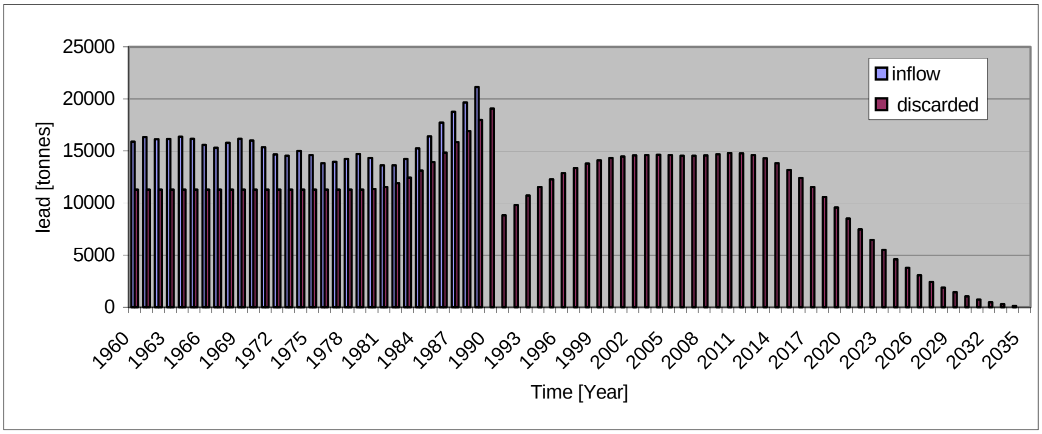

Figure 6.21: The inflow and the discarded outdoor cable sheathing

6.4.3 Total lead in cable sheathing (indoor, outdoor)

Figures 6.22 and 6.23 show the total inflow and outflow of lead in the stock-in-use of cable sheathings. Figure 6.24 shows the fate of the discarded lead sheathing: 75% of the discarded cable sheathings is recycled, while the remaining amount of cable sheathing is left in the environment. The figures do not differ much from those in figure 6.21, due to the fact that the amount of indoor cable sheathings is much smaller than the amount of outdoor cable sheathings.

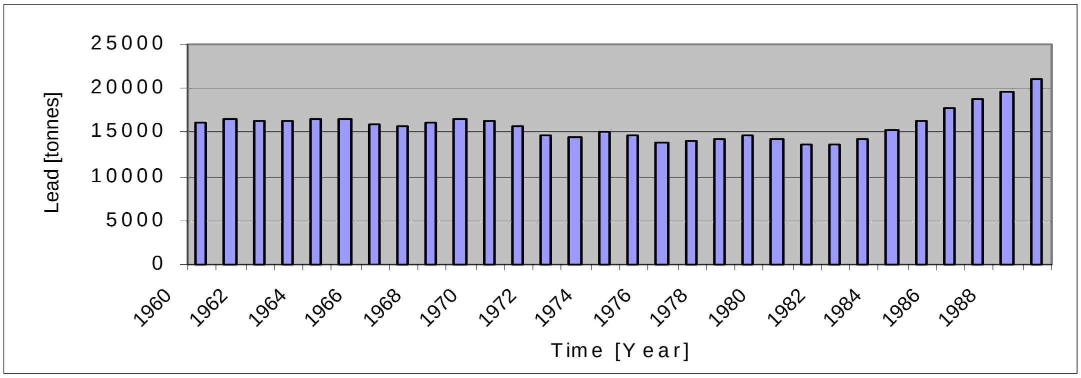

Figure 6.22: The inflow of cable sheathings

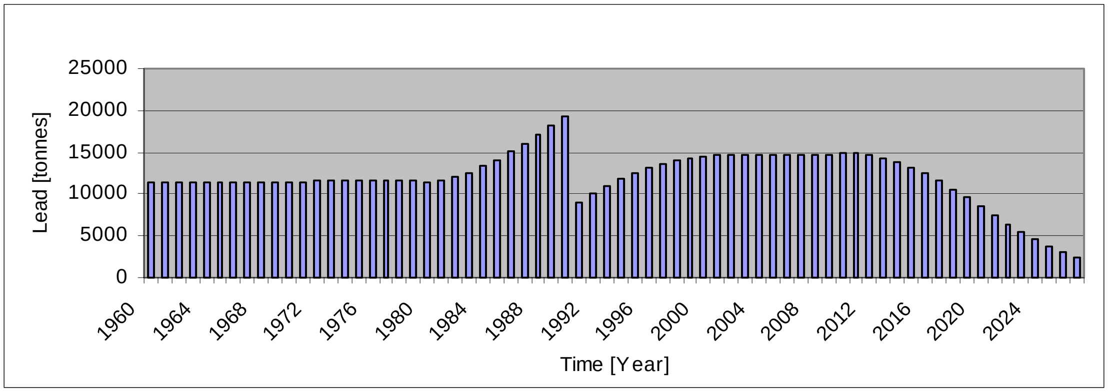

Figure 6.23: The discarded cable sheathings

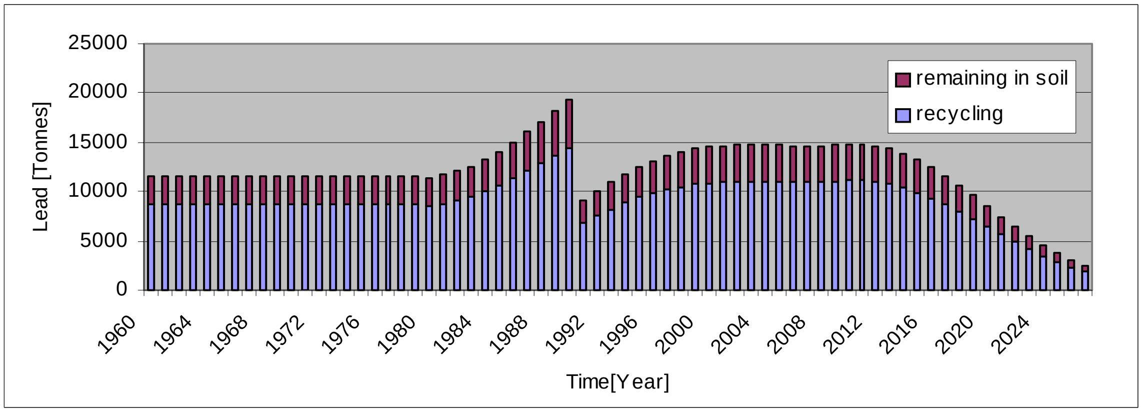

Figure 6.24: The recycled, landfilled, and incinerated cable sheathing

6.5 Cathode ray tubes

6.5.1 Televisions CRT's

6.5.1.1 Stock of televisions CRT's

Stock of lead in televisions CRT's from 1975 through 1999 is calculated based on the stock of televisions multiplied by an average amount of lead in each television (2 kg). Stock of television is calculated as the number of household multiplied by the percentage of those owned televisions (CBS). The difference between the calculated stocks in two consecutive years is the net inflow as given by equation 25.

$$\textit{Net inflow} = S(t+1) - S(t) = \textit{Inflow}(t) - \textit{Outflow}(t) \qquad (25)$$

6.5.1.2 Outflow of televisions CRT's

The outflow of lead from 1976 through 1990 is the discarded lead from the stock in the base year 1975. Assuming that this stock will finish in 15 years, equation 26 is used to calculate the outflow.

$$F^{out}disc(t) = \alpha * S(1975) \qquad (26)$$

$$\alpha = 1/15 \qquad (27)$$

The discarded outflow from 1986 through 1995 is calculated based on the inflow from 1976 through 1985 assuming Weibull distribution of the life span. The outflow from 1996 through 2005 is calculated based on the inflow from 1986 through 1995. The minimum life span is 10 years, the maximum is 25 years and the most likely life span is 15 years.

6.5.1.3 Inflow of televisions CRT's

The inflow of lead from 1976 through 1999 is calculated as the net inflow plus the outflow as given by equation 28.

$$\textit{Inflow}\ (t) = S(t+1) - S(t) + \textit{Outflow}\ (t) \qquad (28)$$

6.5.1.4 Future inflow of televisions CRT's

The past inflow of televisions CRT's has been tested with the different socio-economic variables such as GDP, per head GDP, and population growth. The results show that the correlation between the inflow and these variables are either very low or have the wrong sign as the case with the population growth with the exception of the correlation with the population growth with a time lag of 3 years which eventually can be used in the model. However, we analyse the relation between the stock of televisions CRT's and the socio-economic variables. The results indicate a strong and significant correlation between the stock and all of these variables, however, when two variables are combined in the regression model, the overall correlation goodness does not improve compared with the single variable models. The complete analysis is given in appendix B. Therefore, the stock will be calculated on the basis of the population size till 2030 using equation 29 and the future inflow of televisions CRT's will be calculated based on the future stock and the future net inflow.

$$Stock = -1.19002*10^{7} + (1.17641*10^{6}*pop) \qquad (29)$$

The inflow from 1996 through 2005 is calculated from the outflow from 1996 through 2005 and the net inflow, the inflow from 2006 through 2015 is calculated from the outflow from 2006 through 2015, and the inflow from 2016 through 2025 is calculated from the outflow from 2016 through 2025.

The outflow from 2006 through 2015 is calculated using the inflow from 1996 through 2005 and a Weibull distributed life span and by using the inflow 2006 through 2015, the outflow from 2016 through 2025 can be calculated

Figure 6.25 shows the past and future inflow and outflow of televisions CRT's.

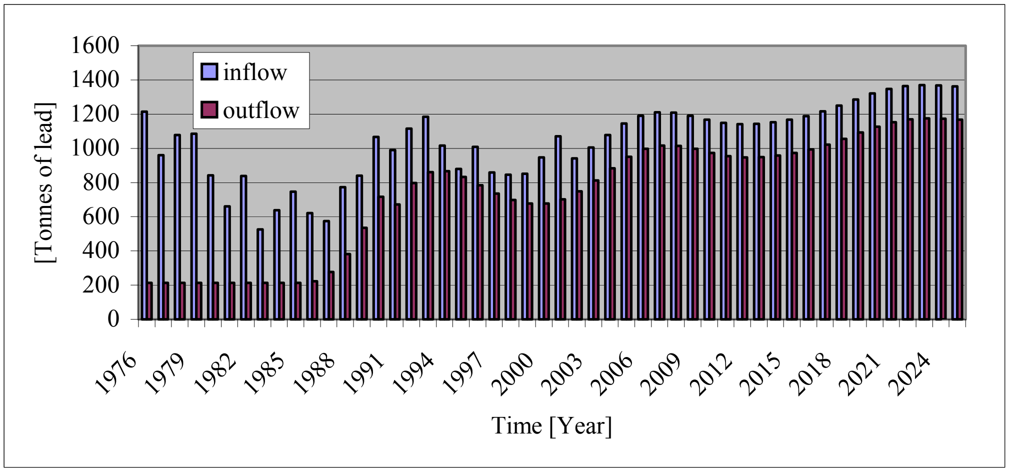

Figure 6.25: Past and future inflow and outflow of televisions CRT's.

6.5.1.5 Waste management of televisions CRT's

The discarded outflow from the stock of products-in-use will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of CRT's is about 50% of the discarded stream. The stream of final waste is split between landfill 40% and incineration 10%. The results are shown in figure 6.26.

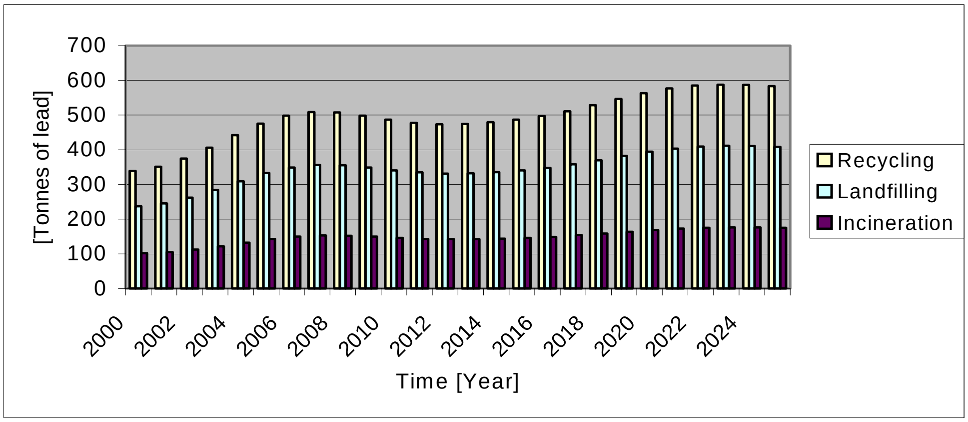

Figure 6.26: Recycled, landfilled, and incinerated streams of CRT's

6.5.2 Household computers CRT's

6.5.2.1 Stock of household computers CRT's

Stock of lead in household computers CRT's from 1987 through 1999 is calculated as the stock of computers multiplied by an average amount of lead in each computer (2 kg). Stock of household computers is calculated as the number of household multiplied by the percentage of those owned computers (CBS). The difference between the calculated stocks in two consecutive years is the net inflow as given by equation 25.

6.5.2.2 Outflow of household computers CRT's

The outflow from 1988 through 2002 is the discarded lead from the stock in the base year 1987. Assuming that this stock will finish in 15 years, equations 26 and 27 are used to calculate the outflow. The discarded outflow from 1998 through 2007 is calculated based on the inflow from 1988 through 1997 assuming a Weibull distributed life span. The minimum life span is 3 years, the maximum is 12 years and the most likely life span is 10 years.

6.5.2.3 Inflow of household computers CRT's

The inflow of lead from 1988 through 1999 is calculated from the net inflow plus the outflow as given by equation 28.

6.5.2.4 Future inflow of household computers CRT's

The past inflow of household computers CRT's has been tested with the different socio-economic variables such as GDP, per head GDP, and population growth. The results show that the correlation between the inflow and these variables are either very low or have the wrong sign as the case with the population growth with the exception of the correlation with the GDP with a time lag of 3 years which eventually can be used in the model. However, we analyse the relation between the stock of household computers CRT's and the socio-economic variables. The results indicate a strong and significant correlation between the stock and all of these variables, however, when two variables are combined in the regression model, the overall correlation goodness does not improve compared with the single variable models. The complete analysis is given in appendix B. Therefore, the stock will be calculated on the basis of the population size till 2030 using equation 30 and the future inflow of household computers CRT's will be calculated based on the future stock and the future net inflow.

$$\boldsymbol{Stock = -4.27752*10^7 + (2.94248*10^6*pop)} \qquad \textbf{(30)}$$

The inflow from 1998 through 2007 is calculated from the outflow from 1998 through 2007 and the net inflow, the inflow from 2008 through 2017 is calculated from the outflow from 2008 through 2017, and the inflow from 2018 through 2027 is calculated from the outflow from 20018 through 2027.

The outflow from 2008 through 2017 is calculated using the inflow from 1998 through 2007 and Weibull distributed life span, and by using the inflow 2008 through 2017, the outflow from 2018 through 2027 can be calculated
Figure 6.27 shows the past and future inflow and outflow of household computers CRT's.

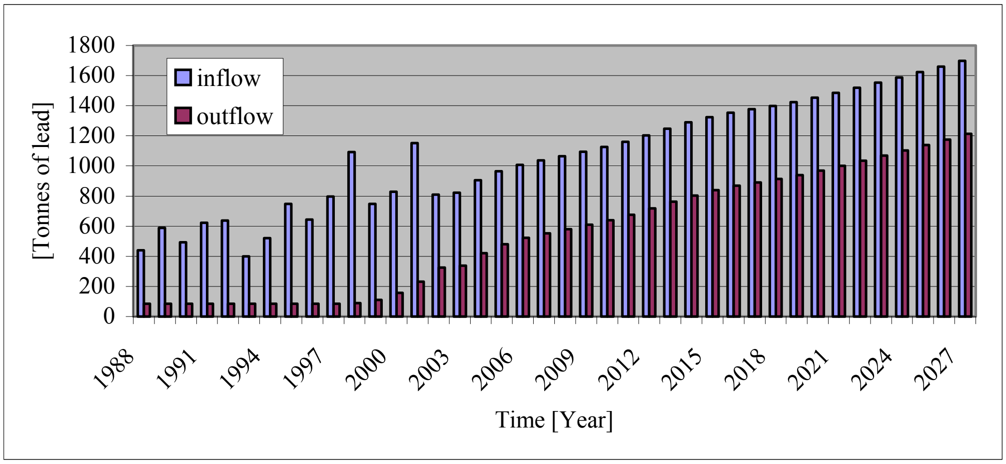

Figure 6.27: Past and future inflow and outflow of household computers CRT's

6.5.2.5 Waste management household computers CRT's

The discarded outflow from the stock of products-in-use will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of CRT's is about 50% of the discarded stream. The stream of final waste is split between landfill 40% and incineration 10%. The results are shown in figure 6.28.

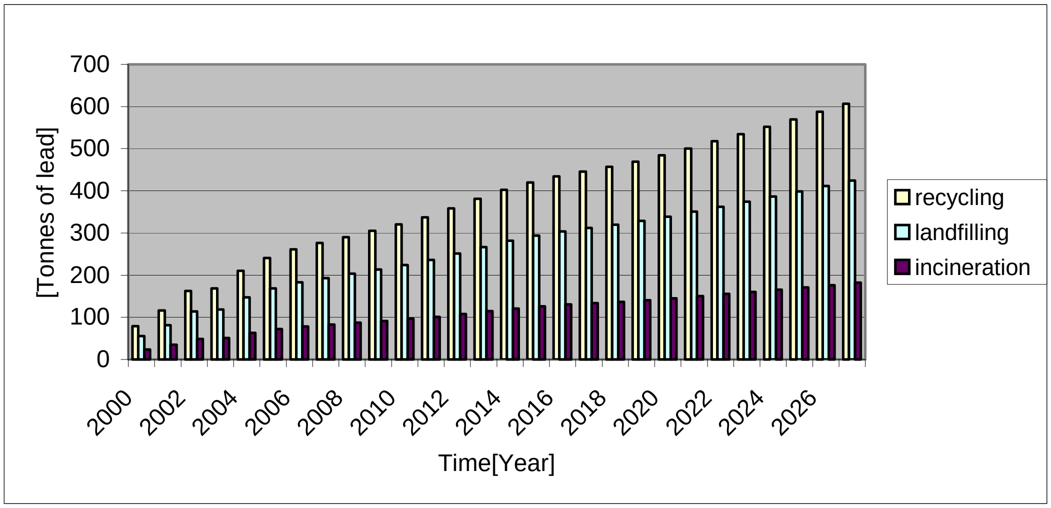

Figure 6.28: Recycled, landfilled, and incinerated streams of CRT's

6.5.3 Office computers CRT's

6.5.3.1 Stock of office computers CRT's

Stock of lead in office computers CRT's from 1988 through 1999 is calculated as the stock of computers (CBS) multiplied by an average amount of lead in each computer (2 kg). The difference between the calculated stocks in two consecutive years is the net inflow as given by equation 25.

6.5.3.2 Outflow of office computers CRT's

The outflow from 1989 through 2003 is the discarded lead from the stock in the base year 1988. Assuming that this stock will finish within 15 years, equations 26 and 27 are used to calculate the outflow. The discarded outflow from 1998 through 2008 is calculated based on the inflow from 1989 through 1998 assuming a Weibull distributed life span. The minimum life span is 3 years, the maximum is 12 years and the most likely life span is 10 years.

6.5.3.3 Inflow of office computers CRT's

The inflow of lead from 1989 through 1999 is calculated as the net inflow plus the outflow as given by equation 28.

6.5.3.4 Future inflow of office computers CRT's

The past inflow of office computers CRT's has been tested with the different socio-economic variables such as GDP, per head GDP, and population growth. The results show that the correlation between the inflow and these variables are very low. Therefore, we analyse the relation between the stock of office computers CRT's and the socio-economic variables. The results indicate a strong and significant correlation between the stock and all of these variables. The best model was the one with the population size. The complete analysis is given in appendix B. Therefore, the stock will be calculated on the basis of the population size till 2030 using equation 31 and the future inflow of office computers CRT's will be calculated based on the future stock and the future net inflow.

$$Stock = -2.61957 \times 10^{7} + (1.82787 \times 10^{6} \times pop) \quad (31)$$

The inflow from 1999 through 2008 is calculated from the outflow from 1999 through 2008 and the net inflow, the inflow from 2009 through 2018 is calculated from the outflow from 2009 through 2018, and the inflow from 2019 through 2028 is calculated from the outflow and the net inflow.

The outflow from 2009 through 2018 is calculated using the inflow from 1999 through 2008 and Weibull distributed life span, and by using the inflow 2009 through 2018, the outflow from 2019 through 2028 can be calculated.

Figure 6.29 shows the past and future inflow and outflow of offices computers CRT's.

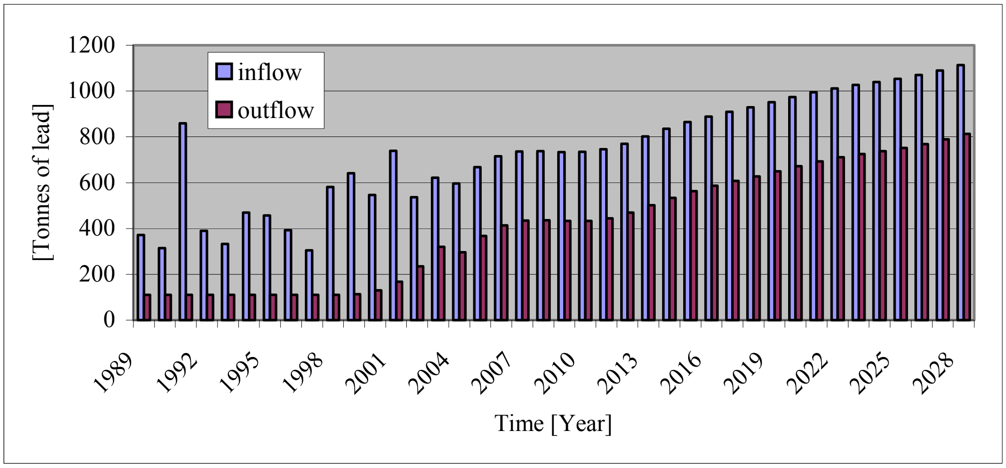

Figure 6.29: Past and future inflow and outflow of office computers CRT's.

6.5.3.5 Waste management office computers CRT's

The discarded outflow from the stock of products-in-use will be partly recycled and partly will end up in the final waste treatment, either on landfill sites or in incineration plants. The recycling percentage of CRT's is about 50% of the discarded stream. The stream of final waste is split between landfill 40% and incineration 10%. The results are shown in figure 6.30.

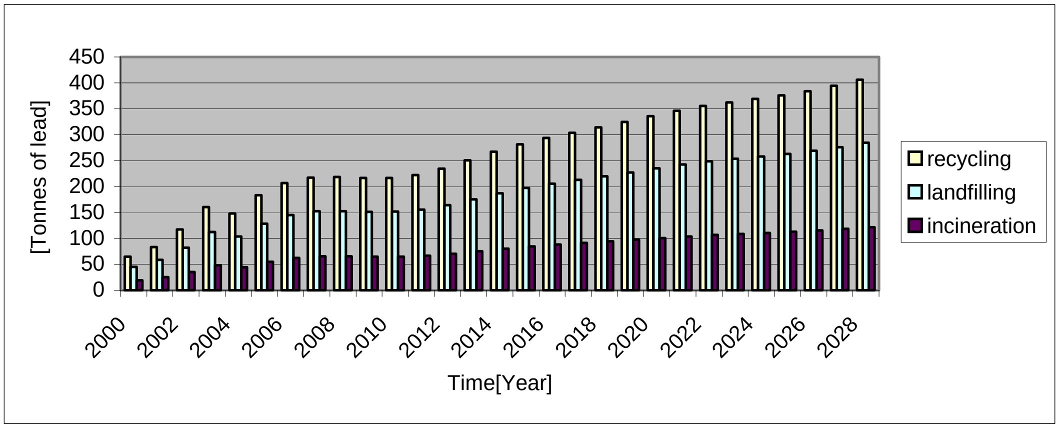

Figure 6.30: Recycled, landfilled, and incinerated streams of CRT's

6.6 Small vehicles computers

6.6.1 Electronics

6.6.1.1 The inflow of electronics

The inflow of electronics into the stock of the products-in-use is the amount of electronics corresponding to the amount of vehicles (new registration and second hand vehicles) (CBS, 1987-2000). Figure 6.31 shows the inflow of electronics in the period 1987-2000.

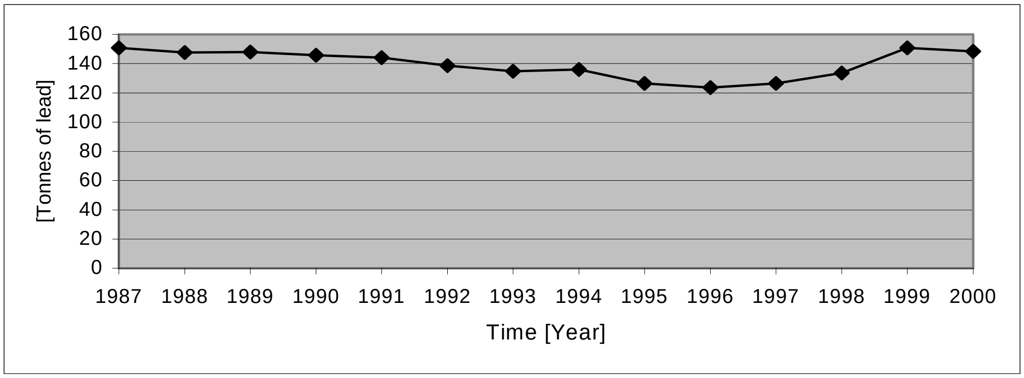

Figure 6.31: The inflow of electronics

6.6.1.2 A model equation of the inflow of electronics

The inflow of electronics has been tested with the different factors such as GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B. The following mode is used to calculate the inflow. Figure 6.32 shows a comparison between the calculated and measured inflow.

$$Inflow = 109.01 + (352.698 * popG\ 75) \qquad (32)$$

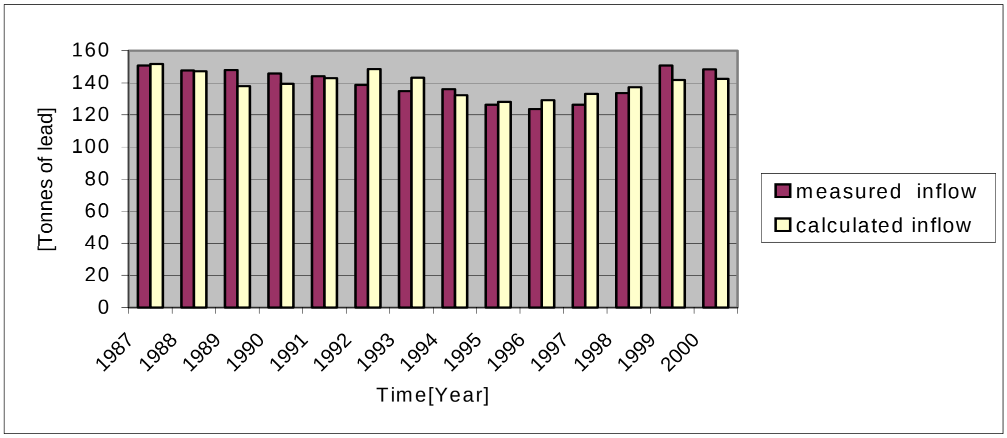

Figure 6.32: Measured and calculated inflow of electronics

6.6.1.3 Future inflow of electronics

The future inflow of electronics is calculated based on equation 32 and the projections of the population.

6.6.1.4 Future outflow of electronics

The outflow of electronics from the stock of the products-in-use is the amount of the discarded electronics with the discarded vehicles. No emission during use of electronics. The future discarded electronics is calculated based on the future inflow and a Weibull distribution of the life span of vehicles. The minimum life span is 2 years, the maximum is 20 years and the most likely value is 12 years.
Figure 6.33 shows the past and future inflow and discarded outflow of electronics.

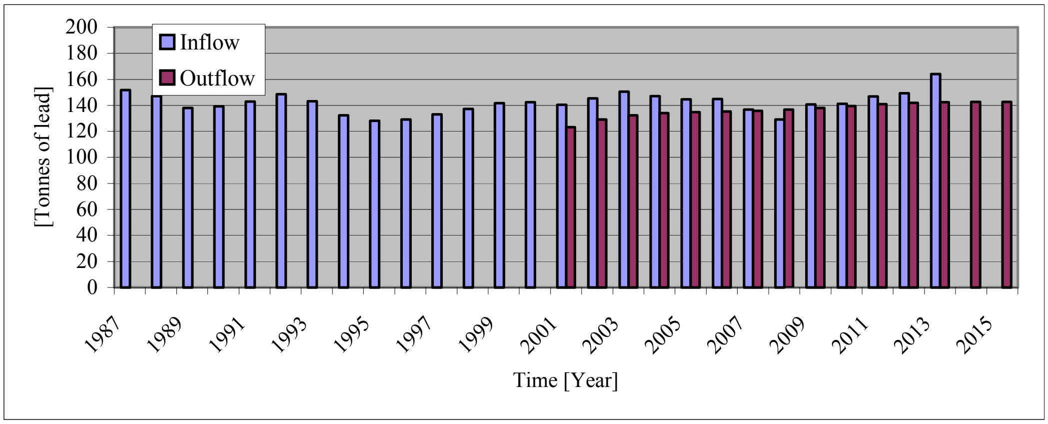

Figure 6.33: Past and future inflow and discarded outflow of electronics

6.6.1.5 Waste treatment of electronics

The outflow from the product-in-use will end up in the final waste treatment either on landfill sites or in incineration plants. The recycling percentage of electronics is 0%. The stream of final waste is split between landfill 75% and incineration 25%. The results are shown in figure 6.34.

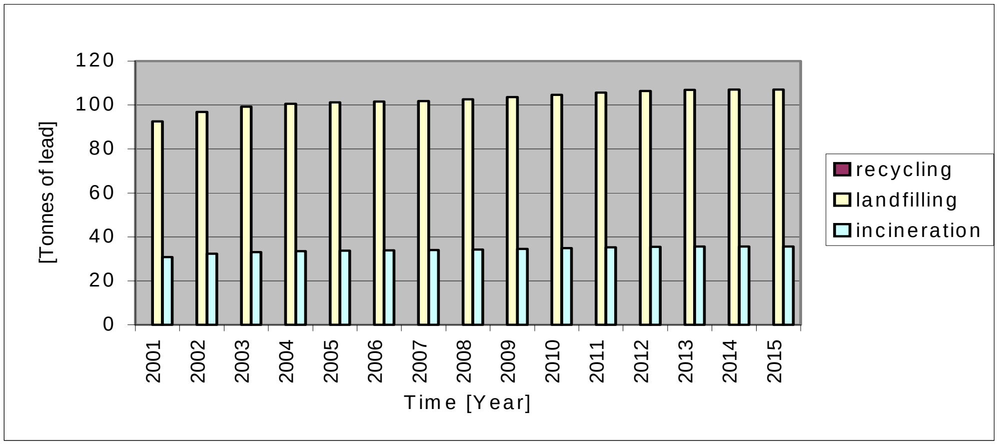

Figure 6.34: Waste streams of electronics.

6.6.2 Bronze, bearings and bushings

6.6.2.1 The inflow of bronze, bearings, and bushings

The inflow of bronze, bearings and bushings into the stock of the product-in-use of the Dutch economy is the amount of these products corresponding to the amount of vehicles (new registration and second hand vehicles) (CBS, 1987-2000). Figure 6.35 shows the inflow of bronze, bearings and bushings in the period 1987-2000.

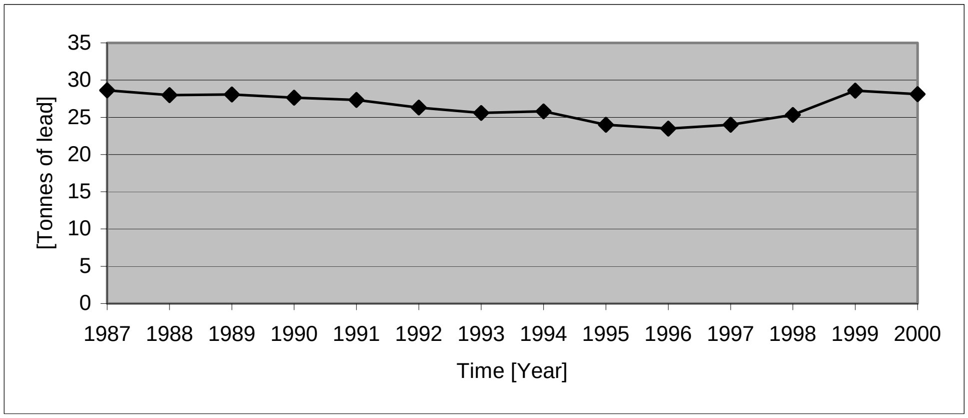

Figure 6.35: The inflow of bronze, bearings and bushings

6.6.2.2 A model equation of the inflow of bronze, bearings, and bushings

The inflow of bronze, bearing and bushings has been tested with the different factors such as the GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B. The following mode is used to calculate the inflow. Figure 6.36 shows a comparison between the calculated and measured inflow.

Inflow = 20.685 + (66.925 * popG 75) ***(33)***

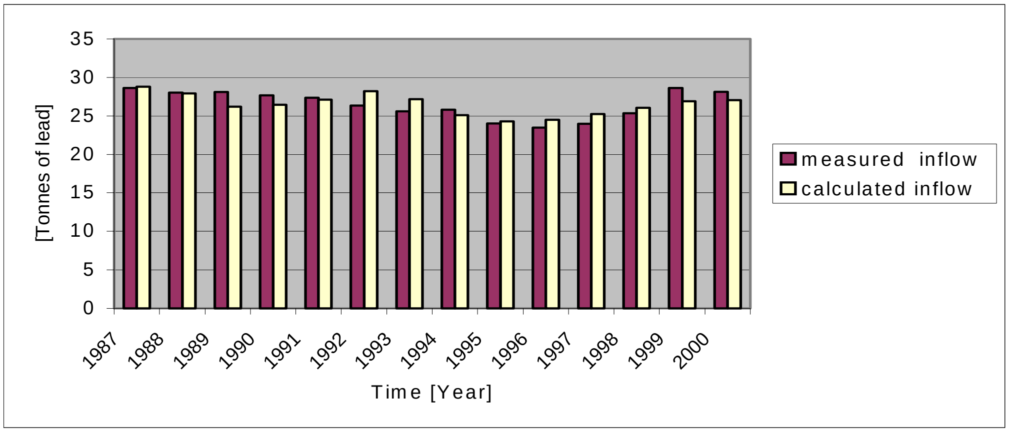

Figure 6.36: Measured and calculated inflow of bronze, bearings, and bushings

6.6.2.3 Future inflow of bronze, bearings, and bushings

The future inflow of bronze, bearings and bushings is calculated based on equation 33 and the projections of the population.

6.6.2.4 Future outflow of bronze, bearings, and bushings

The outflow of bronze, bearings and bushings from the stock of the product-in-use is the amount of the discarded bronze, bearings and bushings with the discarded vehicles. No emissions occur during use of these products. The future discarded bronze, bearings and bushings is calculated based on the future inflow and a Weibull distribution of the life span of vehicles. The minimum life span is 2 years, the maximum is 20 years and the most likely value is 12 years.

Figure 6.37 shows the past and future inflow and discarded outflow of bronze, bearings and bushings.

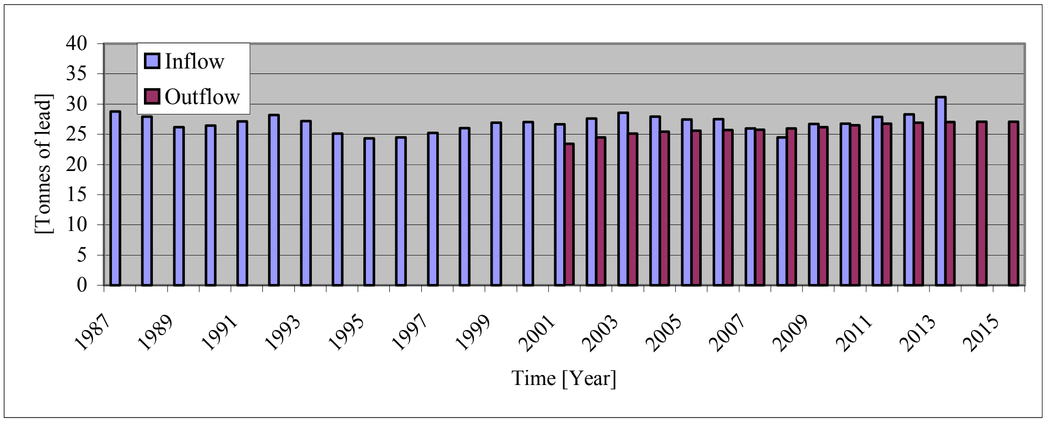

Figure 6.37: Past and future inflow and discarded outflow of bronze, bearings, and bushings

6.6.2.5 Waste treatment of bronze, bearings, and bushings

The outflow from the product-in-use will end up in the final waste treatment either on landfill sites or in incineration plants. The recycling percentage of bronze, bearings and bushings is 0%. The stream of final waste is split between landfill 75% and incineration 25%. The results are shown in figure 6.38.

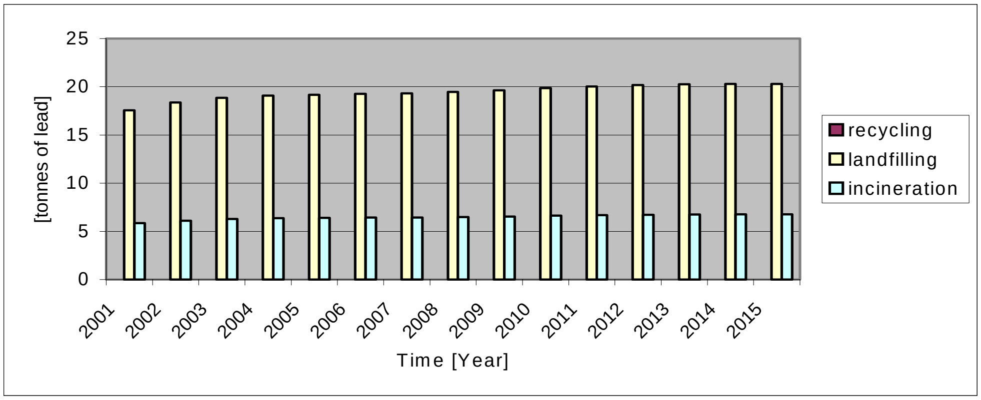

Figure 6.38: Waste streams of bronze, bearings, and bushings

6.6.3 Glazes

6.6.3.1 Inflow of glazes

The inflow of glazes into the stock of product-in-use of the Dutch economy is the amount of glazes corresponding to the amount of vehicles (new registration and second hand vehicles) (CBS, 1987-2000). Figure 6.39 shows the inflow of glazes in the period 1987-2000.

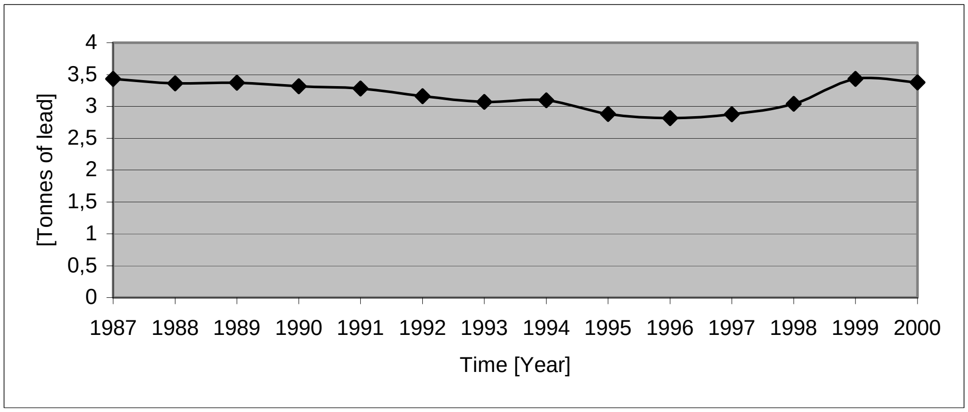

Figure 6.39: The inflow of glazes

6.6.3.2 A model equation of the inflow of glazes

The inflow of glazes has been tested with the different factors such as the GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B. The following mode is used to calculate the inflow. Figure 6.40 shows a comparison between the calculated and measured inflow.

Inflow = 2.482 + (8.031 * popG 75) ***(34)***

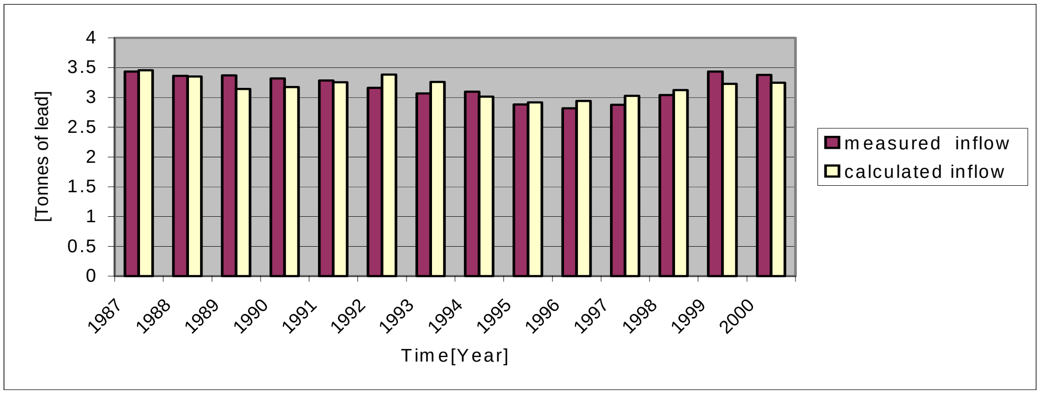

Figure 6.40: Measured and calculated inflow of glazes

6.6.3.3 Future inflow of glazes

The future inflow of glazes is calculated based on equation 34 and the projections of the population.

6.6.3.4 *Future outflow of glazes*

The outflow of glazes from the stock of product-in-use is the amount of the discarded glazes with the discarded vehicles. No emission during use of glazes. The future discarded glazes are calculated based on the future inflow and a Weibull distribution of the life span of vehicles. The minimum life span is 2 years, the maximum is 20 years and the most likely value is 12 years.
Figure 6.41 shows the past and future inflow and discarded outflow of glazes.

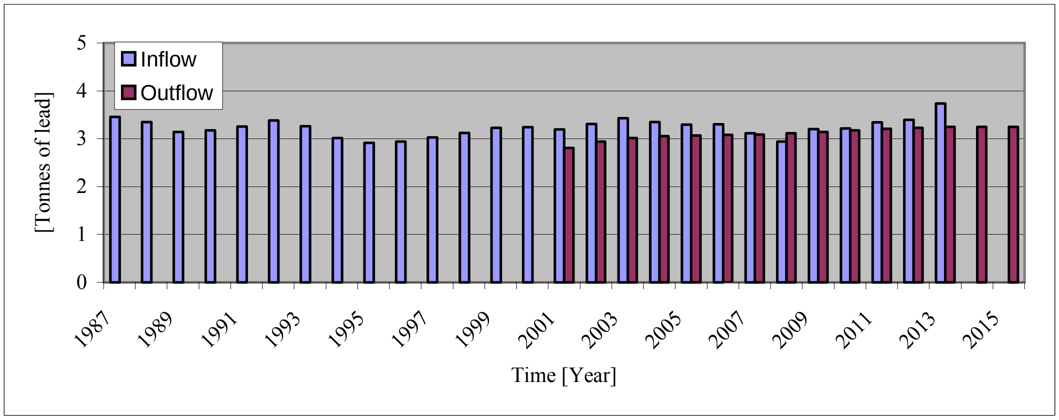

Figure 6.41: Past and future inflow and discarded outflow of glazes

6.6.3.5 *Waste treatment of glazes*

The outflow from the product-in-use will end up in the final waste treatment either on landfill sites or in incineration plants. The recycling percentage of glazes is 0%. The stream of final waste is split between landfill 75% and incineration 25%. The results are shown in figure 6.42.

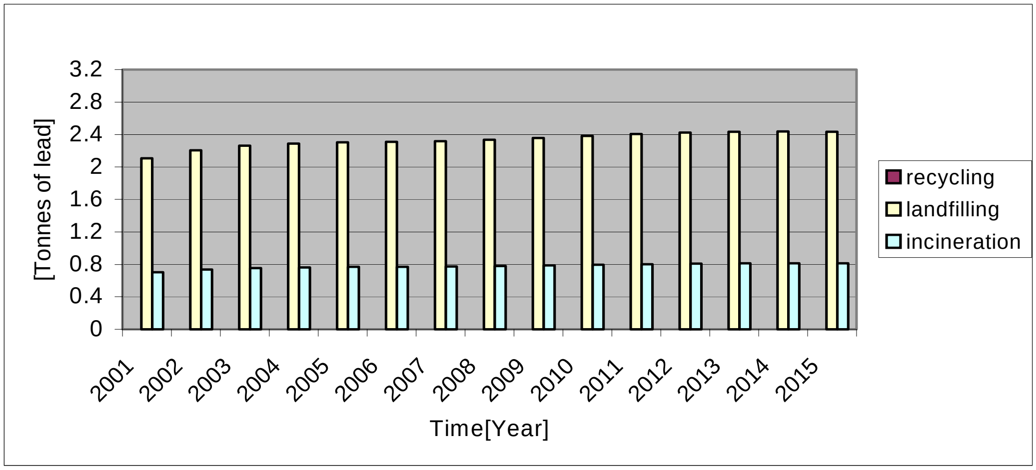

Figure 6.42: Waste streams of glazes

6.6.4 Light bulbs

6.6.4.1 Inflow of light bulbs

The inflow of light bulbs into the stock of product-in-use of the Dutch economy is the amount of light bulbs corresponding to the amount of vehicles (new registration and second hand vehicles) (CBS, 1987-2000). Figure 6.43 shows the inflow of light bulbs in the period 1987-2000.

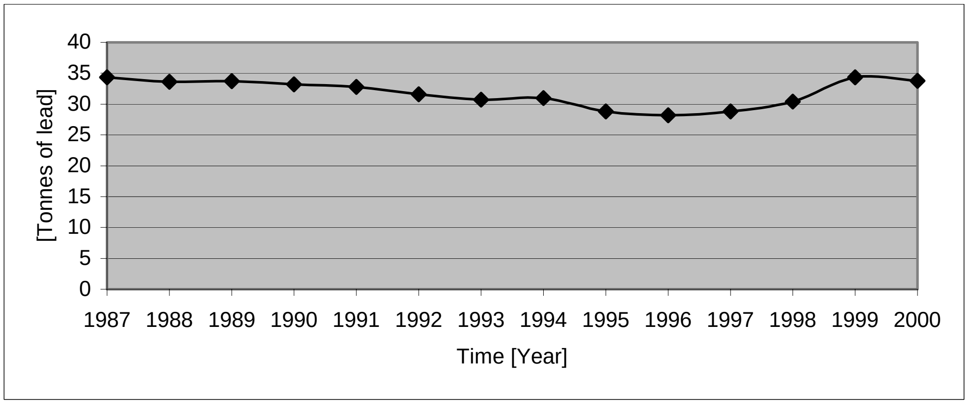

Figure 6.43: The inflow of light bulbs

6.6.4.2 Developing a model equation of the inflow of light bulbs

The inflow of light bulbs has been tested with the different factors such as the GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B. The following mode is used to calculate the inflow. Figure 6.44 shows a comparison between the calculated and measured inflow.

Inflow = 24.822 + (80.3107 * popG 75) **(35)**

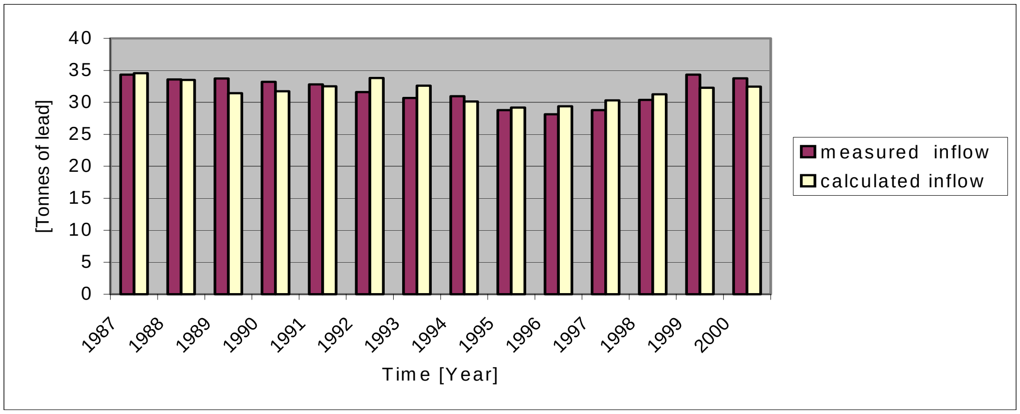

Figure 6.44: Measured and calculated inflow of light bulbs

6.6.4.3 Future inflow of light bulbs

The future inflow of light bulbs is calculated based on equation 35 and the projections of the population.

6.6.4.4 Future outflow of light bulbs

The outflow of light bulbs from the stock of product-in-use is the amount of the discarded light bulbs with the discarded vehicles. No emission during use of light bulbs. The future discarded light bulbs are calculated based on the future inflow and a Weibull distribution of the life span of vehicles. The minimum life span is 2 years, the maximum is 20 years and the most likely value is 12 years.
Figure 6.45 shows the past and future inflow and discarded outflow of light bulbs.

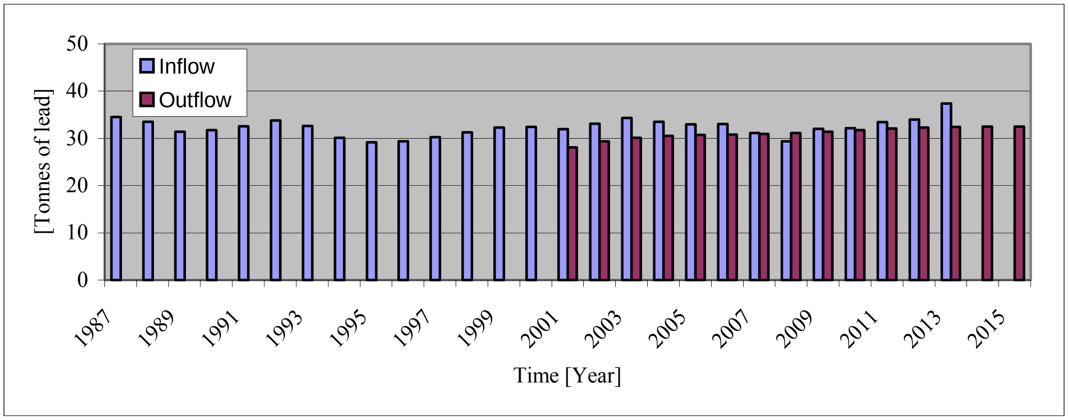

Figure 6.45: Past and future inflow and discarded outflow of light bulbs

6.6.4.5 Waste treatment of light bulbs

The outflow from the product-in-use will end up in the final waste treatment either on landfill sites or in incineration plants. The recycling percentage of light bulbs is 0%. The stream of final waste is split between landfill 75% and incineration 25%. The results are shown in figure 6.46.

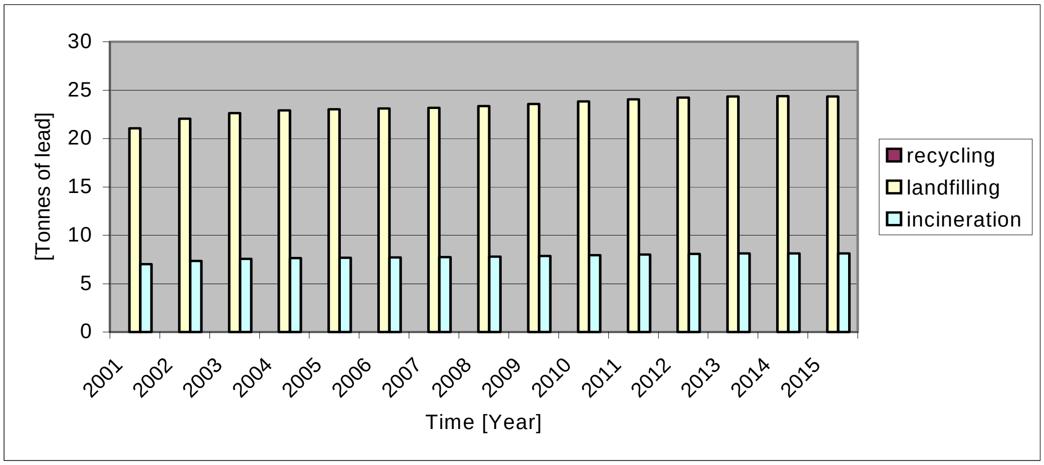

Figure 6.46: Waste streams of light bulbs

6.6.5 Wheel Weights

6.6.5.1 Inflow of wheel weights

The inflow of wheel weights into the stock of product-in-use of the Dutch economy is the amount of wheel weights corresponding to the amount of vehicles (new registration and second hand vehicles) (CBS, 1987-2000). Figure 6.47 shows the inflow of electronics in the period 1987-2000.

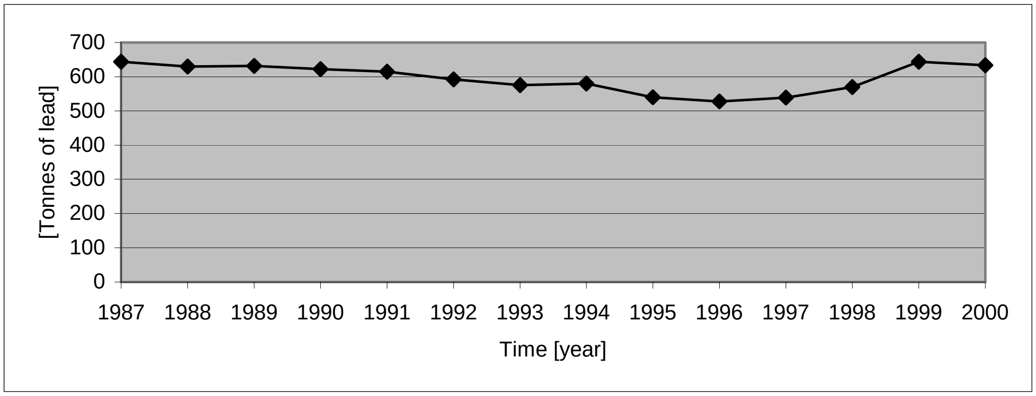

Figure 6.47: The inflow of wheel weights

6.6.5.2 A model equation of the inflow of wheel weights

The inflow of wheel weights has been tested with the different factors such as the GDP, per capita GDP, population size and the time variable. The results of the analysis are shown appendix B. The following mode is used to calculate the inflow. Figure 6.48 shows a comparison between the calculated and measured inflow.

$$Inflow = 465.4 + (1505.82 * popG\ 75) \qquad (36)$$

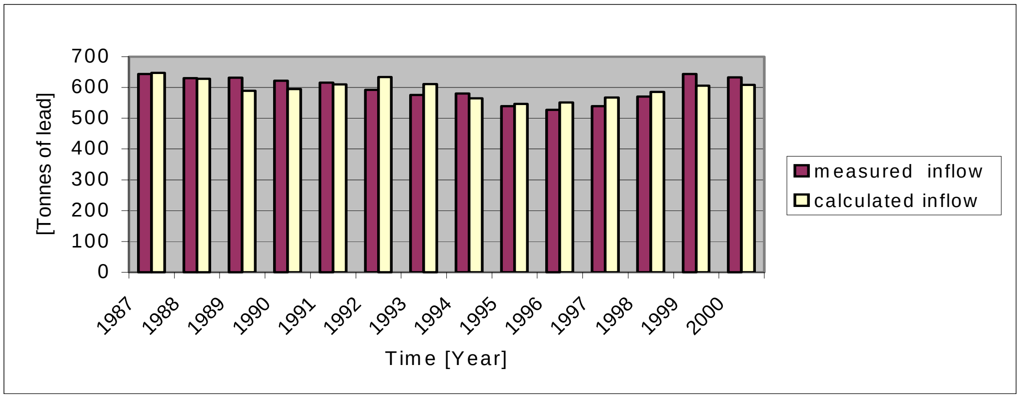

Figure 6.48: measured and calculated inflow of wheel weights

6.6.5.3 Future inflow of wheel weights

The future inflow of wheel weights is calculated based on equation 36 and the projections of the population.

6.6.5.4 Future outflow of wheel weights

The outflow of wheel weights from the stock of product-in-use is the amount of the discarded wheel weights with the discarded vehicles. No emission during use of wheels weights. The future discarded wheel weights are calculated based on the future inflow and a Weibull distribution of the life span of vehicles. The minimum life span is 2 years, the maximum is 20 years and the most likely value is 12 years.
Figure 6.49 shows the past and future inflow and discarded outflow of wheel weights.

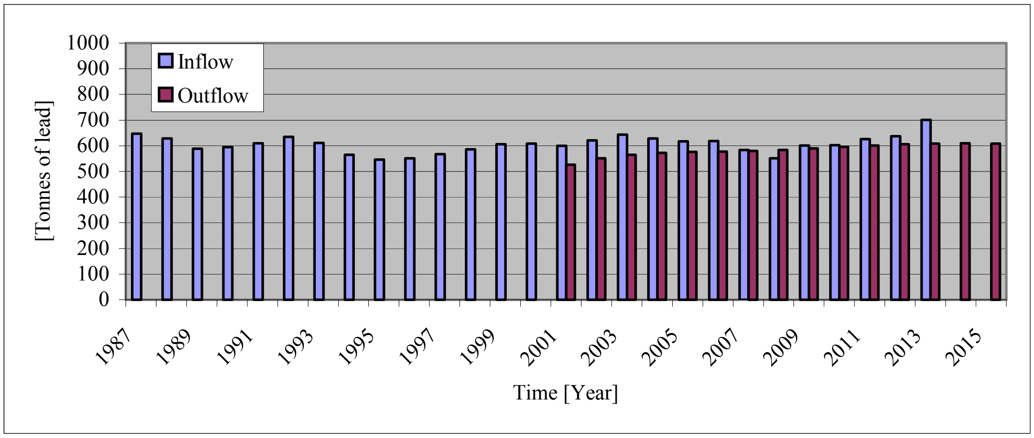

Figure 6.49: Past and future inflow and discarded outflow of wheel weights

6.6.5.5 Waste treatment of wheel weights

The outflow from the product-in-use will be partly recycled and partly will end up in the final waste treatment either on landfill sites or in incineration plants. The recycling percentage of wheel weights is 50%. The stream of final waste is split between landfill 35% and incineration 15%. The results are shown in figure 6.50.

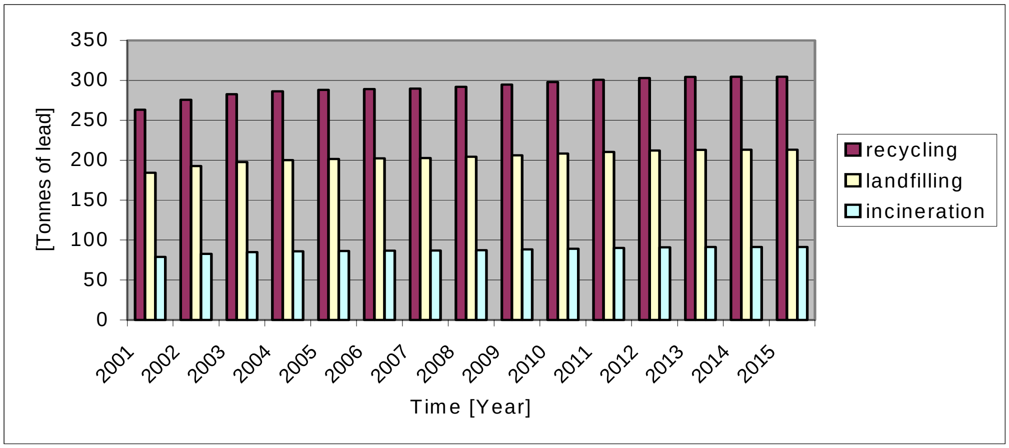

Figure 6.50: Waste streams of wheel weights

6.7 Non-intentional use of lead

In addition to its intentional use, lead is present in several products as a contaminant. Lead occurs naturally in trace concentrations in fossil fuels and in phosphate rock. Via phosphate fertiliser it enters the agricultural chain and accumulates there, leading to significant concentrations in manure. As a result of processing of lead containing waste, it also occurs in residues of waste management such as sewage sludge, compost and products of incineration, i.e. fly ash and bottom ash. These residues sometimes are put to use again. The lead thus enters a secondary, non-intentional life cycle. Fly ash and bottom ash, for example, are used as materials in road construction. It is difficult, if not impossible, to establish a relationship between the use of such secondary materials and economic variables. On the one hand, the supply of these materials is not dependent on any demand, they are a by-product of other processes which in their turn also cannot be associated with an economic demand. On the other hand, they are somehow inter linked within the economic system. If these materials weren't there, others would have been used which would have to be purchased. They thus replace resources. In this report no attempt will be made to capture the use of these materials in economic terms. Still, these non-intentional uses cannot be ignored from an environmental point of view and therefore cannot be left out of a lead stock model. As an example, the use of lead containing bottom ash and fly ash from waste incineration in road construction is specified in this section. Since roughly 1980, bottom ash is utilized as aggregate for road construction and fly ash is utilized in asphalt. In this section the presence of lead as a contaminant in road construction materials will be discussed.

6.7.1 Past inflow of lead in road construction materials

The past inflow of lead into the stock of road construction materials from 1980 through 2000 is estimated based on the mixed solid waste incinerated stream and the quantities of bottom ash and fly ash being applied in road construction, combined with data on the lead content of these streams. The information on the utilized stream of bottom ash and fly ash from 1988 through 2000 is taken from (VVAV, 2001). Before 1988, no data is available. We assume that the use started in 1980, and that the utilized amount of bottom ash in the Netherlands before 1988 is the same as the amount in 1988. The lead content in bottom ash is assumed to be 1500 mg lead/kg ash, and in fly ash 4000 mg lead/kg, based on (Kosson et al., 1996). Figure 6.51 shows the amount of lead in utilized bottom and fly ash from 1988 through 2000 in the Netherlands calculated in this manner.

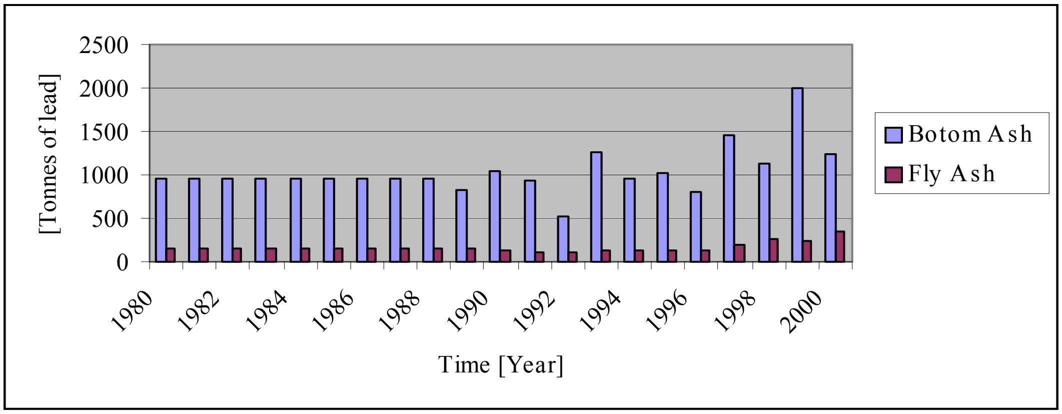

Figure 6.51: The amount of lead in utilized bottom and fly ash from 1988 through 2000 in the Netherlands.

6.7.2 Future inflow of lead in road construction materials

The estimate of the future inflow of lead in bottom and fly ash cannot be calculated in a manner similar to what has been applied for the intentional applications of lead. Instead, the inflow is estimated as a result of the future stream of lead into the waste phase, and assumptions about the waste treatment processes especially the distribution over incineration, landfill and recycling.

Incineration input

The input to the incineration plants originates from three sources:

- the waste stream of lead containing products discarded from the stock-in-use
- the waste materials from the recycling plants
- the fraction of the produced sewage sludge that is incinerated.

By far the largest source is the outflow of discarded lead applications out of the stock of products in use. This figure is taken from the combined sections 6.1 - 6.6, where it is calculated for each application. The input from the recycling plants is unknown, but probably small. Here, it is ignored. The input from sewage sludge originates mainly from the corrosion of lead sheets. Of this corrosion, roughly 50% goes directly to soil, while the other 50% enter the sewage system. Of this 50%, virtually all ends up in the sewage sludge (Tukker et al., 2001). Sewage sludge is disposed of in different manners. About half is used as a soil improves (44%). Of the remainder, most is landfilled (53%). About 3% of the total sewage sludge stream is incinerated (Renner, 2000). This leads to the following estimate of the input into incineration:

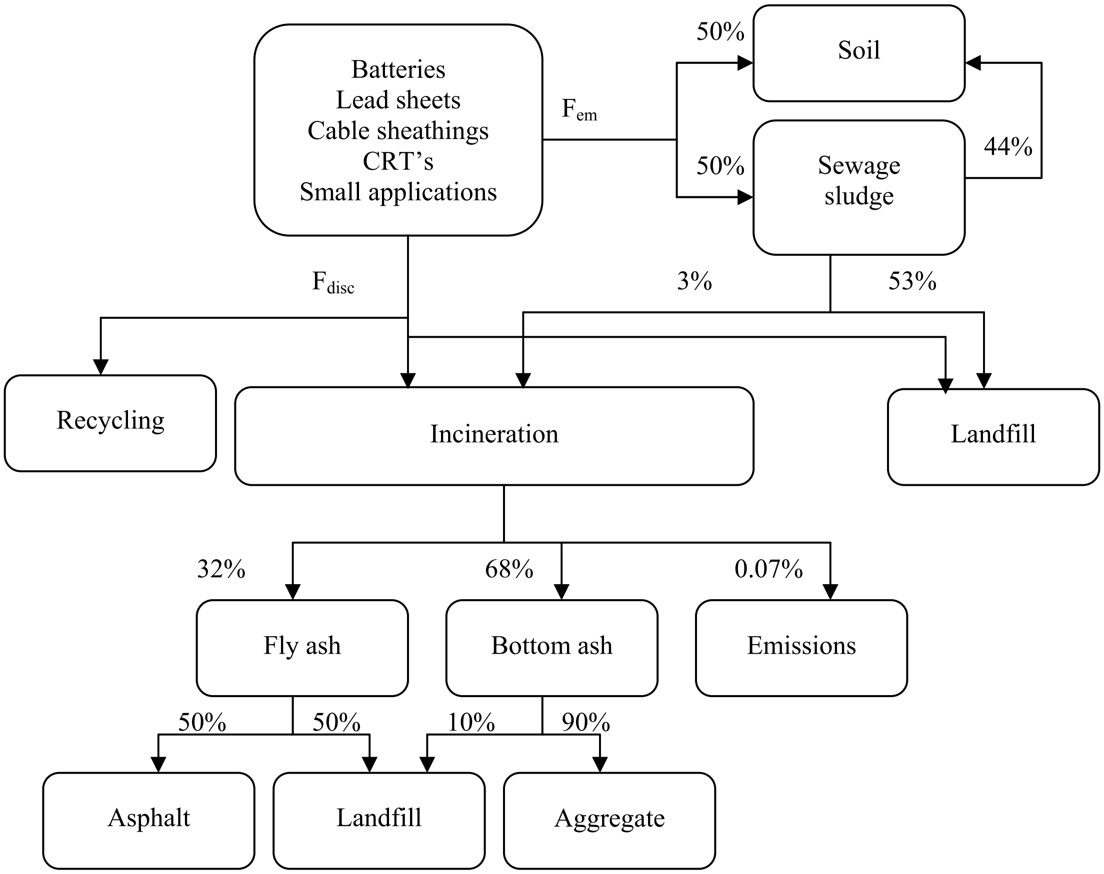

Figure 6.52: The input and output of the incineration and the utilization of the incineration output

Incineration output

The output of the incineration plants is the residue of the incineration process: bottom ash (85%) and fly and combined ash (15%) (Sloot, 1996). Based on the lead content in bottom ash (1500 mg lead/kg) and fly ash (4000 mg lead/kg), lead in the final stream of bottom ash will be 68% and in the final stream of fly ash will be 32% of the lead in the incinerated stream. There is also a small emission to air, which amounts to about 0.07% of the input according to Tukker et al. (2001).

Bottom ash and fly ash are partly utilized and partly landfilled. At present, about 90% of the bottom ash produced in the Netherlands is utilized as an aggregate for road construction (Sloot, 1996) and about 50% of the fly ash is utilized in asphalt (Sakai et al., 1996). These present figures are assumed to be valid for the future as well.

The utilization of bottom ash as aggregate and fly ash in asphalt is shown in figures 6.53 and 6.54.

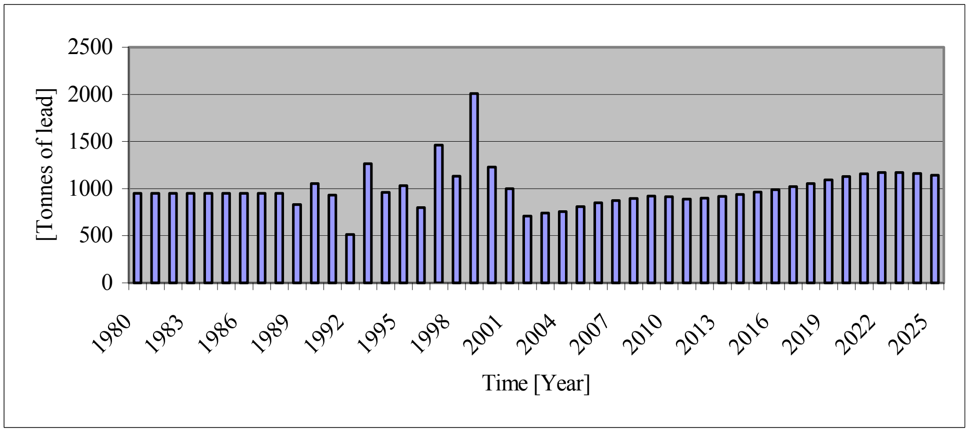

Figure 6.53: Past and future utilization of bottom ash as aggregate in the Netherlands

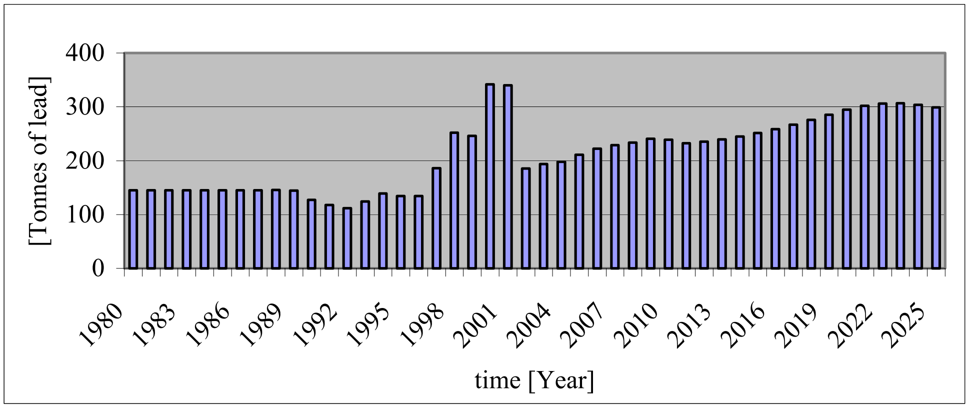

Figure 6.54: Past and future utilization of fly ash in asphalt in the Netherlands

The time series show some strange bumps around the year 2000, especially the figure for fly ash. One should keep in mind that the model for calculating past flows is different from that for the future flows. Combined with the uncertainties in both models, this may be the cause of the bumps. It would have been better to calculate the flows in the same manner for the whole period, but this was not possible since measured data do not exist for the future, while waste stream calculations for all the different applications have not been made for the past. Another possibility is that the high figures for 2000 and 2001 are coincidental. There are some indications that this is indeed the case - sometimes, the ashes are kept for a number of years to be applied at a later date.

6.7.3 Past and future outflow of lead in road construction materials

Outflows of lead out of stock can, just as for the other applications of lead, occur through the mechanisms of leaching and delay.

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. Experiments are being conducted to establish this (Kosson et al. 1996). In most studies this flow is ignored. Due to lack of data, we also will ignore this flow. That implies that the stock of lead in bottom ash is treated as a sink: no outflow takes place at all.

The stock of roads-in-use theoretically has two outflows of lead through the delay mechanism. One is related to asphalt, which is replaced frequently in the process of maintenance and repair of the roads. The average life span of asphalt on the Dutch roads is unknown. We assume, arbitrarily, an average life span of 10 years. The other outflow is related to the road aggregate. We assume that the aggregate is not being replaced but stays in place as long as the road is there. This flow therefore is connected to the abandonment of roads. This occurs occasionally but very infrequently. Therefore we ignore this outflow.

Therefore, the only outflow accounted for is the outflow of lead in asphalt as given by equation 37.

$$F^{out}disc(t) = F^{in}(t-L) \qquad (37)$$

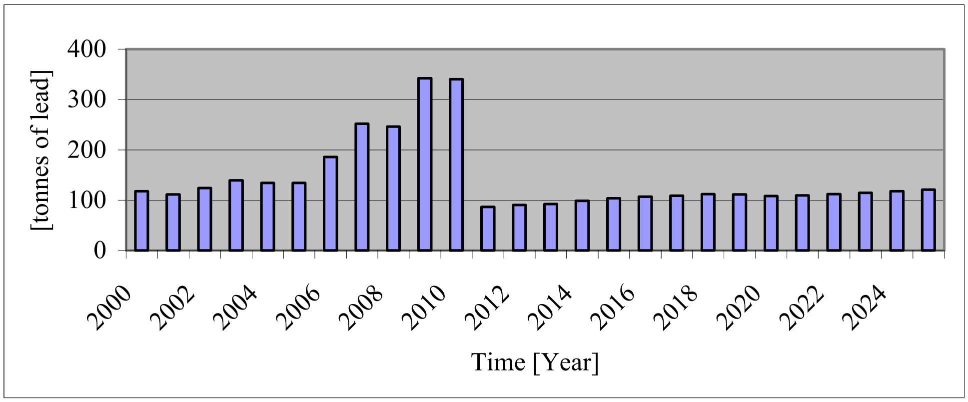

Figure 6.55: Discarded fly ash in asphalt in the Netherlands

6.7.4 Stock of lead in road construction materials

The stock of lead in road construction material in 1988 is estimated based on the amount of bottom and fly ash utilized from 1980 through 1988. The stock from 1988 onwards is estimated as given by the general stock equation, equation 38:

$$S(t+1) = S(t) + F_{in}(t) - F_{out}(t) \qquad (38)$$

S(t+1) is the stock of lead in roads at time t+1, S(t) is the stock at time t, $F_{in}(t)$ is the applied amount of bottom or fly ash in terms of the lead it contains at time (t), and $F_{out}(t)$ is the discarded amount of lead in road materials at time (t). The development of the stocks of lead in bottom ash and fly ash incorporated in road materials is shown in figures 6.56 and 6.57.

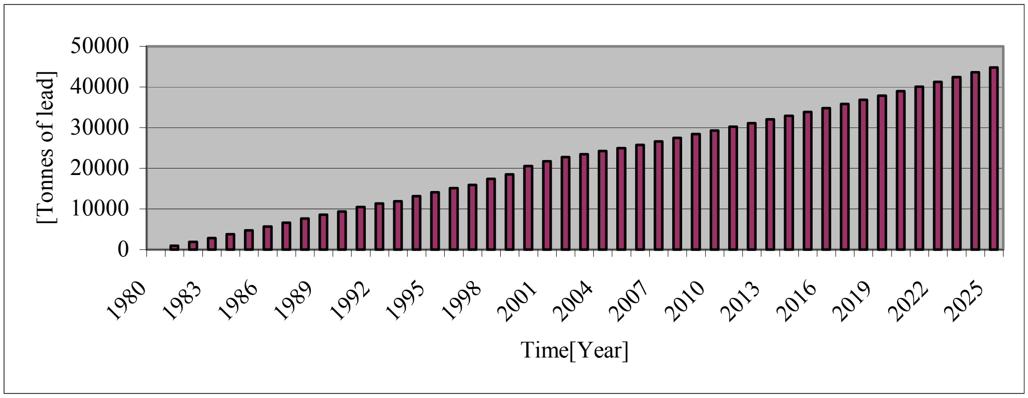

Figure 6.56: Stocks of bottom ash in road construction aggregates in the Netherlands

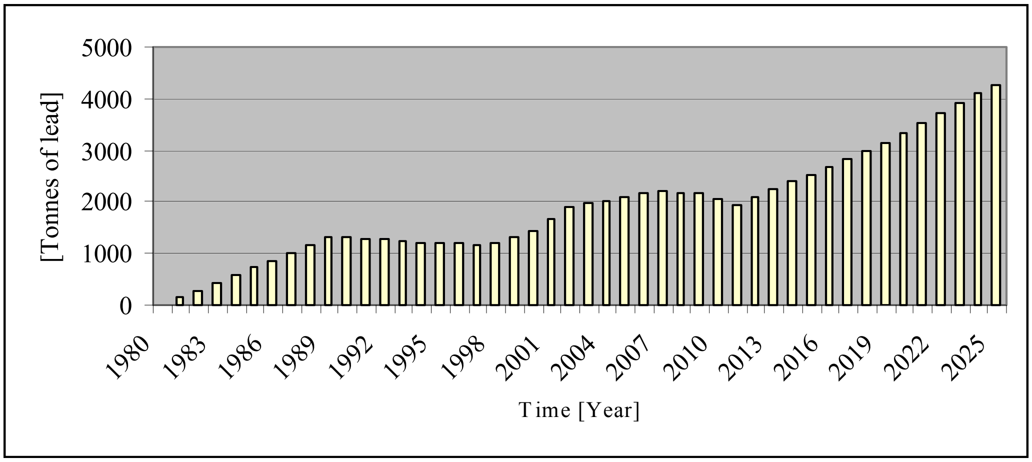

Figure 6.57: Stocks of fly ash in asphalt in the Netherlands

The stocks might be further influenced by recycling. When old asphalt is reused to produce new, a closed loop might evolve leading to ever increasing concentrations of lead. At present, we did not look into this. Such loops and connections are inherent especially to the non-intentional uses. They also can be found in the agricultural system, where the concentrations of lead and other heavy metals in manure are relatively high do to closed loop recycling. These mechanisms have to be taken care of when the stock model is integrated with the substance flow model to form a complete dynamic SFA model.

6.8 General discussion – lead in the Dutch economy

6.8.1 Inflow of lead applications

Lead has been used in the economic system in several applications. By far the dominant application is its use in batteries. The second largest application is its use in rolled and extruded products especially lead sheets in buildings. The third largest application is it's used as pigments especially in cathode ray tubes. In the past, cable sheathing used to be a large application. However the use of lead in cable sheathings is phased out since 1990. Figure 6.58 shows the past and future inflow of lead applications from 1989 to 2025.

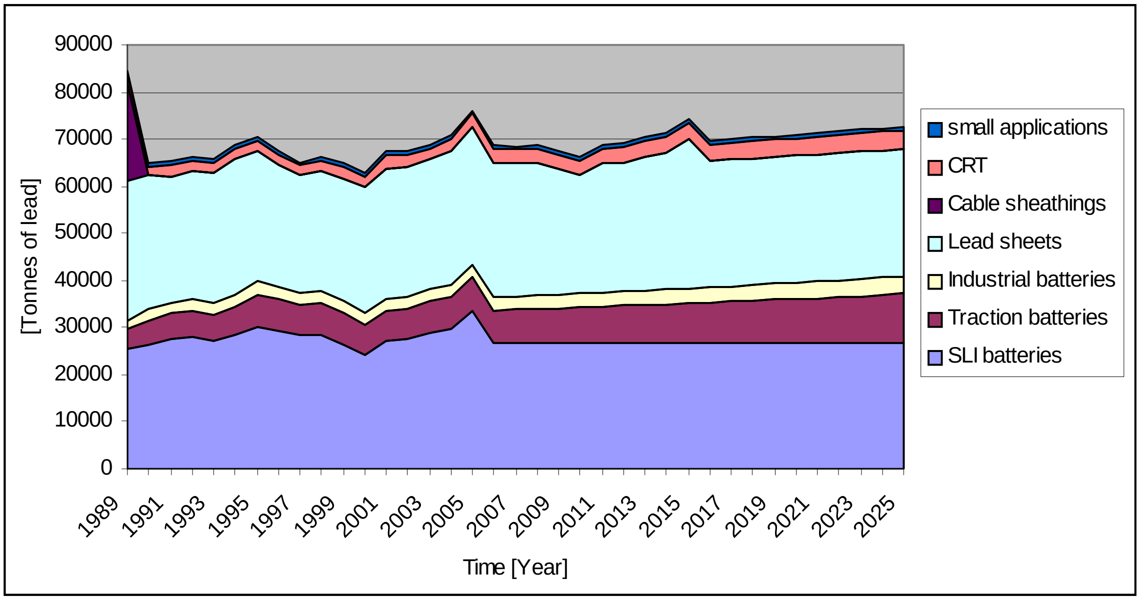

Figure 6.58: Past and future inflow of lead applications

The trend of the SLI batteries inflow can hardly be explained by the increase or the decrease of the Gross Domestic product (GDP). The production of (lead batteries for) new vehicles is expected to fluctuate with the business cycle but this will not be the case for replacement batteries which constitute the largest part of the lead batteries market. This trend could be explained by the population growth with a time delay due to the possible effect of the developments in the population on the vehicles sales market and their use. The analysis of the SLI battery inflow supports this conclusion. The inflow of SLI batteries is expected to decrease between 2000 and 2011 except for the year 2006 and will be stabilize after 2012.

The slightly increasing trend of the inflow of the industrial batteries could be slightly explained by the developments of the population size but could be explained much better by the developments in the per capita income. Per capita income fluctuates in line with the inflow most of the time.

Traction batteries are used in different applications. Each of these has its own behaviour, some of them could be effected by the economic growth and others with the developments in the population. In all, the inflow is increasing over time.

The demand for lead sheets in buildings is directly linked to the housing demand, which is mainly driven by the growing population. In the future, the demand for houses (and consequently lead sheets) is expected to stabilise.

The demand for CRT's is determined by the demand for televisions, household computers and office computers. The demand for televisions is mainly driven by the population growth while the demand for household computers is driven by both, the population growth as well as the economic growth. In the future the demand for computers is expected to increase while the demand for televisions will be slightly increasing.

The demand for the small vehicle applications (electronics, bronze, bushings, light bulbs, wheel weights and glazes) is directly linked to the demand for vehicles which is mainly determined by the population growth and the economic growth.

6.8.2 Outflow of lead applications

The outflow of lead applications is the discarded amount (figure 6.59) and the emissions during use (figure 6.60). The discarded amount of each application is mainly determined by the application's inflow and their life span and the emissions during use by the emission factor and the size of the stock.

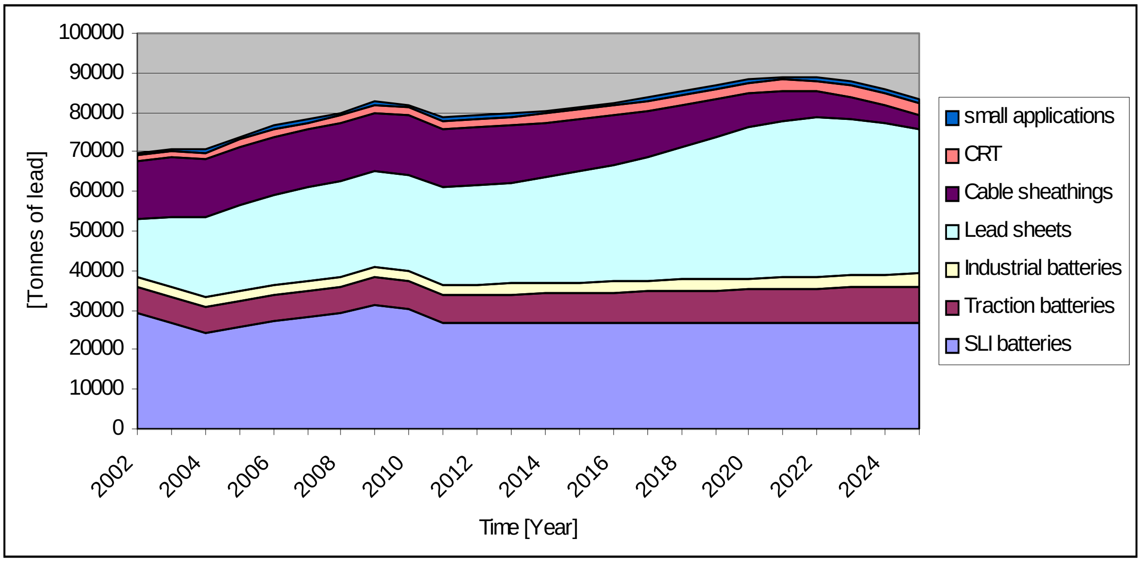

Figure 6.59: Discarded batteries, lead sheets, cable sheathings, CRT's, and small vehicles applications

The discarding of SLI batteries does not show a general trend. This was to be expected since the inflow is quite stable, and the life span of these batteries is short. However, the discarded traction and industrial batteries is expected to increase due to the increase of the inflow and due to their long life span.

The discarding of lead sheets is expected to increase due to the extensive use of lead sheets in the past. Likewise, the discarding of cable sheathings is expected to keep increasing till the year 2010 due to the extensive use of cable sheathing in the past. After

2010 it will start to decrease because it is phased out from some applications in 1970 and from almost all the remaining applications in 1990. However, part of the discarded cable sheathings will remain in the environment.

The discarding of CRT's, electronics, bronze, bushings, light bulbs, wheel weights and glazes is expected to increase due to the extensive use of computers and vehicles and due to the long life span of both, the computers and the vehicles.

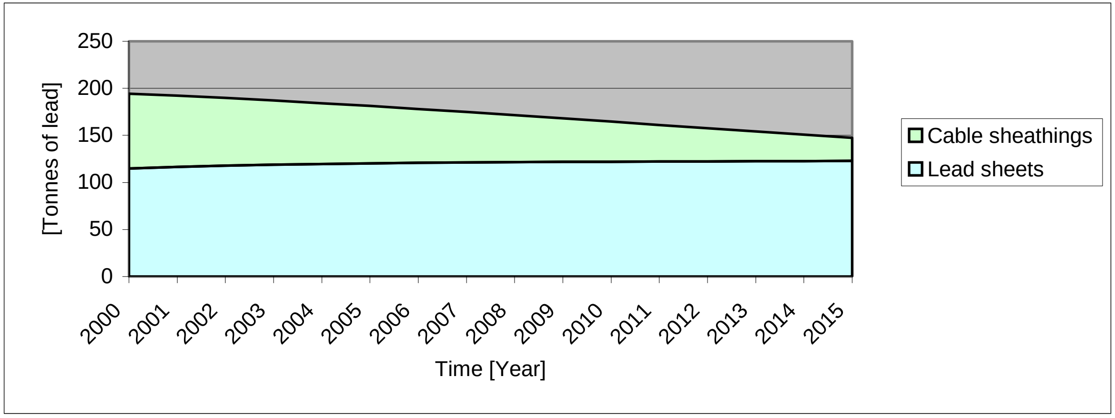

Figure 6.60: The emissions during use of cable sheathing and lead sheets in buildings.

Despite the assumption concerning the recycling (75%), the contribution of cable sheathing to the emissions of lead to the environment is rather high. The remaining amount of cable sheathing in soil is quite high due to the low collection rate and the fact that that lead sheathing has a relatively low commercial value.

Most of the lead applications such as batteries, CRT's and the small vehicle applications have no emissions during their use phase. Most of the emissions therefore are due to the cable sheathings and lead sheets in buildings, which are exposed to the environment. The emissions from the lead sheets are expected to increase in the future due to the expected increase of stocks. The emissions from the cable sheathing stock are expected to decrease slowly over time, as there is no fresh inflow in this stock while part of the old stock is being collected and recycled. The total emissions are expected to decline. However, it should be kept in mind that there are other lead emissions to the environment not originating from the stock of products-in-use, especially related to agriculture and to the incineration of fossil fuels.

6.8.3 Stocks of lead applications

In general, the stock is decreasing in size. Instead of a sink, the stock thus is expected to become a source of lead in the near future. Lead sheet dominates the stock-in-use for a long time to come.

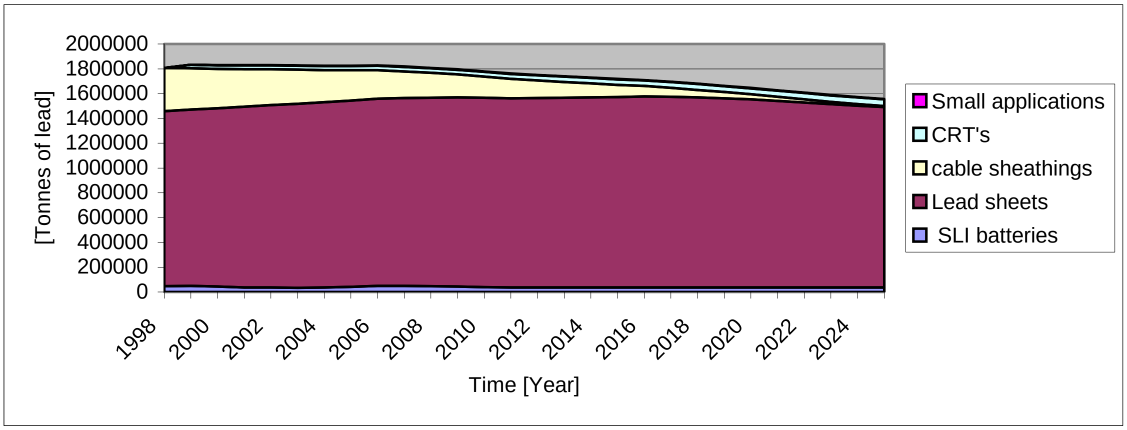

Figure 6.61: Stocks of lead applications in the Dutch economy

6.8.4 Waste treatment of lead applications

Figure 6.62 shows the recycled flows of the lead applications and figures 6.63 and 6.64 show the total waste flows to landfills and incinerators.
At present, the largest contribution to lead recycling is made by SLI batteries. In future, lead sheets are expected to be the largest contributors: the outflow of SLI batteries is expected to stabilise while the outflow of lead sheets will increase. Smaller contributions are made by other batteries - the recycling rate is equally high or even higher, but the lead flow to these applications is smaller. The largest flows to landfill and incineration are related to lead sheets, SLI batteries, and CRT's. This can be explained by the intensive use of both lead sheets and SLI batteries in the past and present: the recycling rate for these applications is quite high, but the amounts are so large that the small percentage of final waste from these applications still amounts to a large quantity compared to others. The CRT's flow is mainly related to the low recycling rate. The future flow of CRT's to landfill and incineration is expected to increase and by 2025 will be almost 20% of the total lead flow to landfills. Flows to incineration and flows to landfill show a rather similar pattern. Only the contribution of lead sheets is different. A larger part of the discarded lead sheets will end up at landfill together with the demolition waste, leaving only a very small fraction to-be-incinerated. The flows of the small vehicle applications (electronics, light bulbs, glazes, wheel weights bronze, bushings and bearings) to landfill and incineration are relatively high compared to their throughput. This high contribution to the final waste stream is mainly due to the very low recycling rate of these applications.

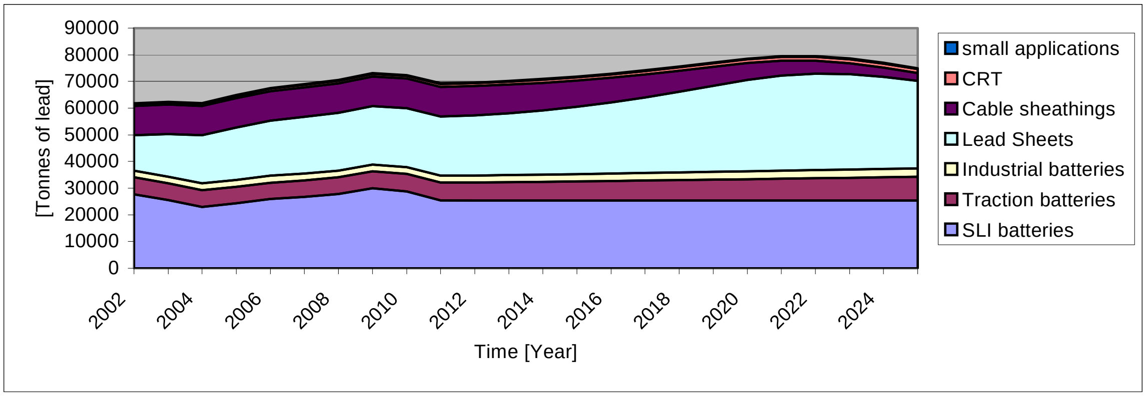

Figure 6.62: Recycled flows of the lead applications

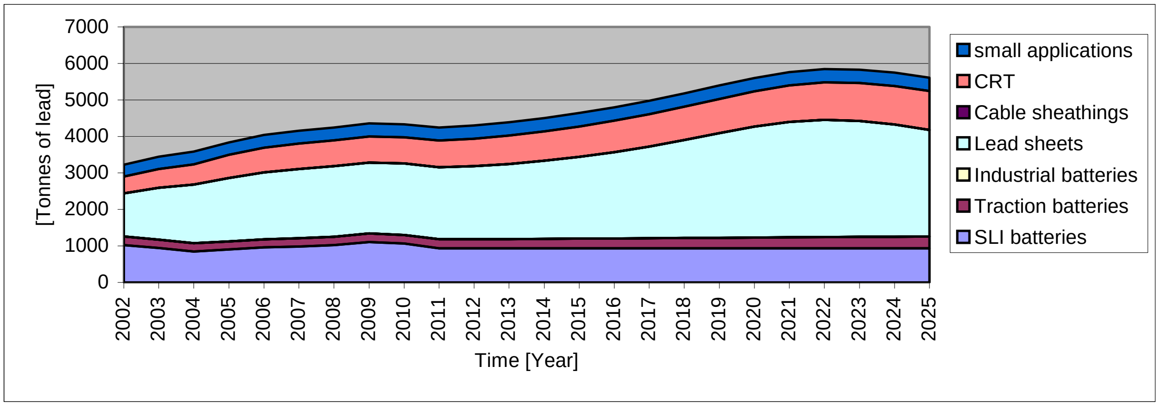

Figure 6.63: Landfilled flow of the lead applications

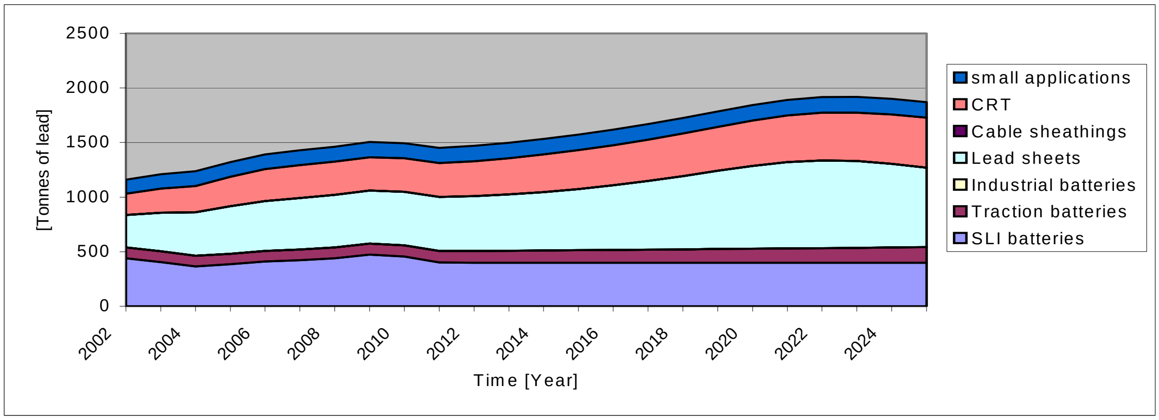

Figure 6.64: Incinerated flows of the lead applications

6.8.5 Future demand for lead and the availability of secondary material

Total inflow and outflow of lead flows

The inflow of lead in the Dutch economy has no general trend, it is neither increasing nor decreasing in a continuous time. Several studies on heavy metals have attempted to find explanatory variables for the trend in lead demand on the regional or global level. Most of them have failed to find such variables. This maybe due to the number of applications which lead has been used in, and the different behaviour of each of these applications. The trend of some of the lead applications could be consistent with the developments in GDP, per capita GDP, some could be effected by the lead price and some other applications could only be explained by the population growth or the population size. Moreover, the time lag between the developments in these factors and the response of the market is sometimes one or two years but in other cases even much longer. When the trend of the inflow of lead to be explained, it has to be explained on a product basis.

The outflow of lead from the consumption-and-use phase is basically the discarded lead containing products and the emissions of lead during use. The discarded lead is expected to increase in the period from 2002 onwards, with a slight dip in 2011 and 2012. This trend in the outflow shape is mainly due to the inflow of different applications and the different life spans of these applications.

Figure 6.65 shows the total inflow and the total outflow of lead out of the Dutch stock of products-in-use. A remarkable development is that the outflow is larger than the inflow from 2002 onwards. This implies that the stock of lead in products is no longer a sink, but has become a source of lead. Due to the magnitude of the stock (figure 6.61) , it can be expected that lead will come out of it for a long time, even in the case that lead applications would phased out altogether. For waste management, this is relevant information.

Although most of the lead applications are recycled, the amount ending up at landfill sites and incineration plants is still considerable. Moreover, there is a significant amount of lead that remains in the environment in old cable sheathings. This hibernating stock still causes diffusive emissions.

The recycled stream of lead is about 88% of the discarded stream, the landfilled stream will increase from 4.6% in the year 2002 to 5.6% in the year 2015, the incineration stream will also increase from 1.6% in 2002 to 1.9% in year 2015. The remaining amount in the soil which almost 5.2% in the year 2002 will decrease to 4% in the year 2015. The future recycled, landfilled, incinerated, emitted and remained lead in the environment are shown in figure 6.66.

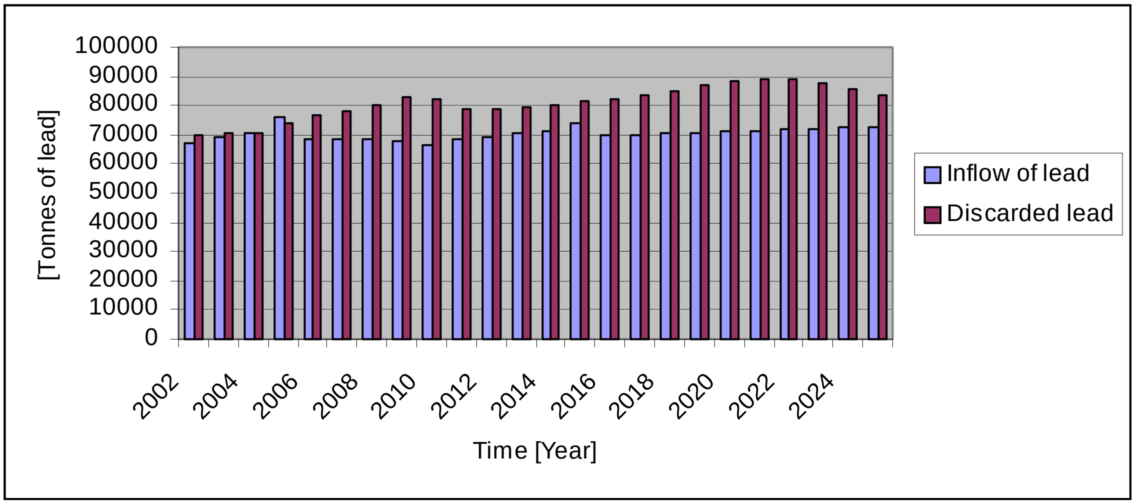

Figure 6.65: The inflow and discarded lead

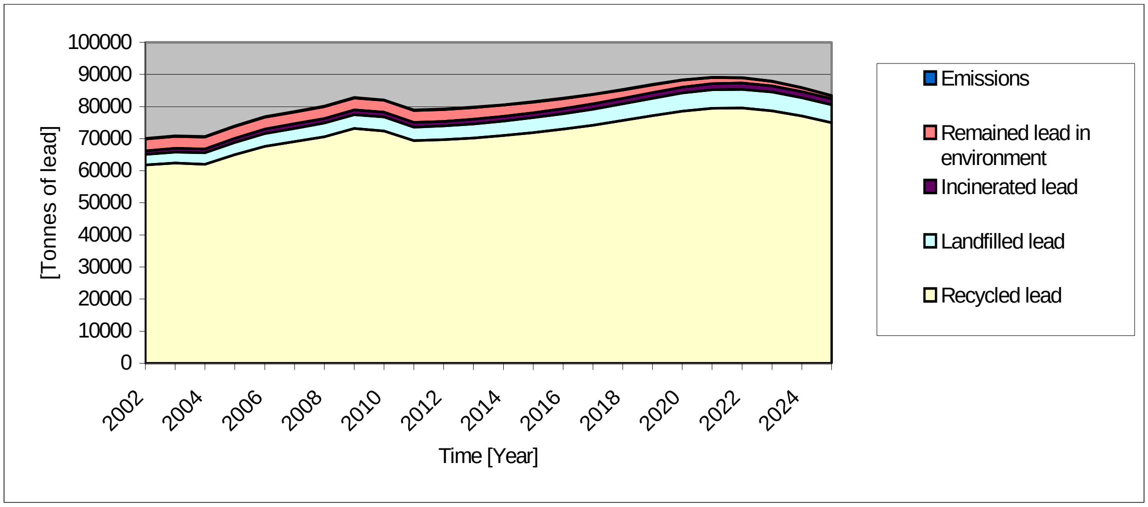

Figure 6.66: The recycled, landfilled, incinerated, emitted, and remained lead in the environment

The future lead demand and the availability of secondary lead

Figure 6.67 shows the future demand for lead applications and the amount of recycled lead. It is clear that in the years from 2002 to 2006, the demand for lead will be more than what could be available from recycling. After 2006, the recycled amount will exceed the demand for lead. This implies that after 2006 the total Dutch demand for lead could be met completely by the generated secondary lead. Since the Dutch economy is very open this need not have large implications. However, when a similar pattern can be found in other countries as well, this would mean that the supply of lead could outgrow the demand. This could have a number of implications. One implication could be a decrease in the lead price. Normally this would lead to an increase in the use, but since lead applications are subject to regulation this might not be so straightforward. On the other hand, it may lead to a decrease in the production of secondary lead, since recycling processes may become less profitable. In turn, this might lead to larger amounts of lead being dumped at landfill sites or being incinerated. This again would lead to larger emissions to the environment. For environmental policy therefore it would be very interesting to know whether or not indeed the supply of lead may be expected to outgrow the demand as a result of the emptying of old stocks-in-use, and if so, how long this emptying process might be expected to go on.

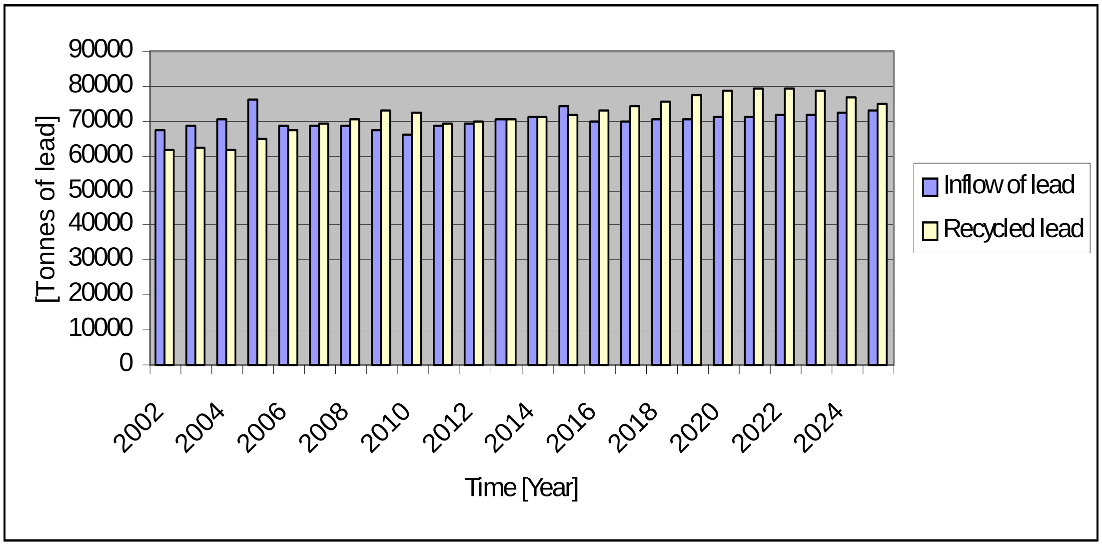

Figure 6.67: The demand for lead and the availability of secondary lead

7 CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

7.1 Conclusions

The model developed and presented in this report is a dynamic substance stock model that combines physical and economic elements. The model is meant to be an integrated part of a dynamic substance flow model, which can be used to estimate future waste and emissions. By combining physical and economic elements into one model, the limitations of the existing economic and material flow models can be bypassed and the strengths combined.

In the model, a distinction is maintained between stocks and flows. In this stock model, the flows are limited to the direct inflows into and outflows out of the stock. They can be the handles for integration of this stock model into a substance flow model. In the chosen setup, there is a mutual influence between stock and flows: the stock is the result of the flows, while at the same time some of the flows are a result of the stock.

The model operates at two levels: the product level and substance level. This enables to overcome the difficulties of modelling the substance stock: often it is not possible to directly model the substance stock because it is built up out of a large number of applications, each showing different behaviour in the economic system. Moreover, it enables to include both product related developments (such as product alternatives, product price, going out of fashion etc.) and substance/material related developments (such as alternative substances fulfilling the same function, the materials price, possibilities for recycling, substance oriented policies etc.). The distinction between stocks and flows enables to account for the impact of delay especially for those applications with a long life span and including both physical and economic elements enables to cover a wide range of factors affecting the dynamic behaviour of the system.

On the product level, all applications of the substance are included. For each product, the inflow into the stock of products-in-use 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. These variables appeared to be sufficient to describe the past inflow, at least for the elaborated case study of lead. The equation used for the past then is transferred to the future, based on expectations about the development of the said variables. For the future, however, some other variables such as substitution and technological developments might be equally important. These are as yet not included in the model. The model forecasts therefore are only valid assuming that no unpredicted changes, such as the development of a completely new substitute, will occur.

The outflow out of the stock of products-in-use is basically determined by two physical processes: leaching and delay. The leaching outflow, emissions during the use of the product 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. Two factors play an important role in determining the accuracy of the outcome of the model, namely the emission factor and the product life span. The emission factor is assumed to be constant and the life span is assumed to be Weibull distributed, however, in reality both are subject to changes.

The model estimates the end-of-life treatment in the future - recycling, landfilling and incineration - based on the assumption that the current distribution of the waste stream over the three destinations will remain the same. This might not be the case in the future due to the fact that these streams are subject to change because of policy, technical, or economic reasons. The model handles these factors as parameters that enable to investigate any other possible scenarios.

The stock model has been applied to the case of lead in the Netherlands. The lead model includes most of the intentional applications of lead, such as batteries, lead sheet, cathode ray tubes and cable sheathings which constitute the largest part of lead use in the economic processes. Some applications, which are important from an environmental point of view, such as ammunition and the existence of lead as a contaminant in the agricultural sector, are not included. Such flow related applications have not been a part of this research but are probably important for the generation of waste and emissions. Combining the lead stock model with a flow model may clear this up.

The total lead demand is modelled on the basis of its individual applications. The demand for the SLI batteries is expected to decrease and then stabilize, however, the demand for both industrial and traction batteries are expected to increase slightly. The demand for lead sheet is expecting to stabilize in the future. The demand for computer monitors CRT's is expecting to increase, however, the demand for televisions CRT's is expecting to stabilize in the future.

The outcomes of the model suggest that the lead stock will in a few years start decreasing over time. Instead of a sink, the stock thus will become a source for lead. For the applications included in the model, lead sheet in buildings will dominate the stock for a long time to come, mainly due to the long life span of lead in those applications. The battery system has the largest in- and outflows. Despite this, it does not contribute much to the stock on the long term, due to the short life span of the batteries. There is a significant amount of lead that remains in the environment in old cable sheathing despite of the assumption on the recycling quantities (75%). This hibernating stock still causes diffusive emissions and will continue to do so for a long time.

Although most of the discarded lead applications are recycled (88% of the discarded stream), the amount ending up at landfill sites and incineration plants is still considerable. The lead flows in waste are expected to increase, and therefore also the flows of lead to incineration and to landfill. However these should not be treated as a final figures, since other sources that contribute to the waste streams have not been investigated: waste from mining and industry, waste from lead applications with a short lifespan, and last but not least loops and cycles within the end-of-life treatment system. This makes especially the figures for landfill quite uncertain.

Another model result is that the lead emissions from the stock of products-in-use are decreasing over time. This is mainly due to the assumption that 75% of the old cable sheathing will be removed from the soil and will be recycled. However, these should not be treated as a final figure since the model quantifies only part of the emissions from the stock and other emissions sources such as the emissions from the extraction, production and waste treatment processes, which required further study, are not included. This implies that the emissions as calculated in Chapter 6 do not at all form a complete picture. At the moment, it is unclear how the emissions from stock compare to the flow related emissions from industry, fossil fuels and agriculture. This will be the subject of future investigations.

For a substance management, the stock model may provide relevant information. The results of this model can be represented in different ways, depending on the policy issue at hand. For example, the contribution of the different applications to landfill or diffusive emissions can be specified over time, which is useful information for a waste prevention or pollution prevention policy. Another example is the future estimate of what will become available for recycling. 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 for 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.

7.2 Discussion

The model described in this report is a dynamic stock model that consists of two sub-models. The first sub-model is the inflow model, which is based on the past inflow into the stock of products-in-use data and a regression model that describes this inflow as a function of socio-economic variables such as GDP, per head GDP, population growth and price. The same model is used to predict the future inflow with projection of the socio-economic variables.

Instead of using a regression analysis, 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. This approach is often taken for example in ecological analyses, where knowledge about the relationships within ecosystems is used to build, for example, a food web or population dynamics model. For such an approach, however, a certain prior knowledge or insight in the system and the relations within is required. Such knowledge is lacking in this case. 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 inflow. This approach has been widely used in environmental as well as economic research.

The approach taken to estimate the inflow has its limitations. The basic idea is that the relationship between the demand and the socio-economic variables will remain in future what it has been in the past. In the above we already remarked that this will not be the case if something new happens, such as the development of new materials or processes of production, use and waste management, or the demand is influenced by specific policy. Changes like that will render the inflow equation useless. Any model results should be regarded in that light. Up to now, no attempts have been made to include trend deviations in the model.

The second sub-model is the outflow model, which is based on the mainly physical mechanisms of leaching and delay. The leaching model estimates the outflow out of the stock due to the emissions during use as a fraction of the stock. The delay model estimates the discarded outflow as a delayed inflow with a Weibull life span distribution. Other distributions are possible. In extreme situations - for example, a very long life span, a very wide or narrow or a very skewed distribution - this may considerably influence the results.

The model operates at two levels, the product and substance level. Two approaches can be used to model the inflow of substances to the stock of products-in-use. The first approach is based on calculating the inflow into the substance stock as the sum of all product inflows, which can be modelled as a function of the socio-economic variables, multiplied by the fraction of the weight that is taken up by the substance. This is the approach taken in this report. A second possible approach is based on calculating the inflow into the substance stock on basis of the substance's economic characteristics, that is, the function fulfilled by the substance in the products. These economic characteristics strongly depend on the physical and chemical properties of the substance, which determine aspects like durability, hardness, resistance to corrosion, protectiveness against radiation, flexibility, colour etc., and they determine whether or by which material the substance in question can be replaced. A first exploration of this approach is given in Chapter 3, but it is not further elaborated here. During the project, the added value of such an approach has been discussed. On the one hand, it is not required to calculate future flows and stocks - the substance stock can be modelled by just adding all product stocks, which seems sufficient. On the other hand, this approach could be a handle to include substitution and technical developments in the model as an addition to the already included socio-economic variables. This remains an interesting issue to explore further in the future.

Another possible level is the material level that the products ultimately are consisted of. Materials dynamic behaviour in the economy is mainly determined by their inflow and outflow characteristics. The inflow of material into the stock of products-in-use is mainly determined by economic factors such as material price and the outflow is mainly determined by the emissions during use and recycling. The material level does not appear in the lead model presented in this study due to the fact that this level does not make difference in the specific investigated applications. It is important however, for the general stock model to operate on the three levels: the substance level, material level and product level when required.

The general stock model like many environmental or economic models, has several sources of uncertainty and as a consequence the model has a doubtful outcome. By definition, models are a representation of aspects of a system considered essential, which represent knowledge of that system in a usable form. This reflects that not everything is included. The uncertainties in the dynamic stock model are due to many sources related to the three models of the system. The uncertainties could be due to disturbances in the model variables or perturbation in the model parameters. Disturbances are mainly from the dynamics in the original equation of the change of the stock as well as the additional relations of the input and/or the output. The inflow in the model is described by a regression model. The explanatory variables in this model may not be correct or may be incomplete. For the future, major changes may happen limiting the applicability of the equation. Some variables may lose importance over time, while others may become more important. The perturbations are mainly due to parameter uncertainty. In the leaching model there may be uncertainties in the estimate of the annual loss fraction, which in reality depend on many factors such as the surrounding atmosphere, the weather, maintenance, and others. In the delay model, the life span is always assumed either as average life span or as life span distributed in time. The estimate of the average life span may be incorrect or liable to change over time. The chosen type of life span distribution or the estimates for minimum and maximum may be inaccurate. In the report, we have identified some of the sources of uncertainties. Possibly there are others. There are some ways to identify and treat model uncertainties, which we have explored briefly. We did not work this aspect out further. Nevertheless it is very important, which implies that much work needs to be done in this area.

7.3 Recommendations

The model in its current situation has many 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:

- On the inflow level, the model includes some of the socio-economic variables, however, some other variables such as substitution and technological developments are not included. These might affect the demand for substances due to phase-out policies, efficiency improvements, the development of new substitutes or the introduction of completely new technologies. Obviously, a model that aims at delivering meaningful estimates of future waste and emissions should include these variables. A first recommendation therefore is to devote attention to the identification and inclusion of trend deviations into the model.

- On the outflow level, the discarded outflow is estimated based on the assumption on the products life span, and the emitted outflow is estimated based on assumption on the emission factors. In order to minimize the uncertainty in the model, it is useful to look in more detail into both the corrosion process and the factors determining the life span of products. This could be done, for example, by comparing the model outcome with real data on the discarded stream and the emissions from corrosion. This would allow for a more accurate prediction.

- 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 end-of-life treatment of discarded products so far has been investigated very partially. The division of the three main waste streams - landfill, incineration and recycling - could change over time and probably is changing over time. Estimates for the future could be influenced by policy, or could be driven by economics or technical developments. The destination of the residues of waste management is also important, especially to identify closed loops. Recycling influences the inflow of new materials. All these loops need to be included in the model. This issue is especially important when integrating the stock model - where inflows and outflows are treated in a limited way - into a flow model. This integration is of vital importance and is strongly recommended.

- For the lead case study, the model does include the largest intentional lead applications such as batteries, lead sheet, cathode ray tubes and cable sheathing. It also includes one of its non-intentional applications, the utilization of the outflow of the incineration (fly and bottom ash) in road construction material. For the purpose of estimating the waste streams, those applications might be sufficient, however for the estimation of the overall emissions, it is necessary to include other applications such as ammunition as one on the intentional use of lead and the existence of lead as a contaminant in the agricultural sector and fossil fuels. These applications are flow-related rather than stock-related, which again illustrates the importance of the integration of the stock model into a flow model.

8 REFERENCES

Bergbäck, B. and Lohm, U., Metals in Society. In: Brune, D. and Chapman, V., (Ed.), The Global Environment - Science, Technology and Management, Scandinavian Scientific Press, Oslo, pp 276-289, 1997.

Central Bureau of Statistics Netherlands (CBS), Production and Trade Statistics, Eurostat, Voorburg, 2000.

Central Bureau of Statistics Netherlands (CBS), Statistisch Jaarboek, Voorburg, 1987-2000.

Guinée, J.B., J.C.J.M. van den Bergh, J. Boelens, P.J. Fraanje, G. Huppes, P.P.A.A.H. Kandelaars, Th.M. Lexmond, S.W. Moolenaar, A.A. Olsthoorn, H.A. Udo de Haes, E. Verkuijlen and E. van der Voet (1999). Evaluation of risks of metal flows and accumulation in eco-nomy and envi-ron-ment. Ecological Economics (30)1: 47-65.

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

International Lead and Zinc Study Group, Principal Uses of Lead and Zinc:1993-1998, ILZSG, London, 2000.

Inter-secretariat Working Group on National Accounts, Eurostat, International Monetary fund (IMF, Organisation for Economic Co-operation and Development (OECD), United Nations, World Bank, System of National Accounts, Luxembourg, 1993

Institute for Ecology and Political Affairs (IEPA), Heavy Metals in Vehicles II, Final Report, 2001

Kandelaars, P, (1998), Material-Product Chains: Economic Models and Applications, Ph.D thesis, Amsterdam.

Kemp, R., (1997), Environmental Policy and Technical Change: a Comparison of the Technological Impact of Policy Instruments, University Press, Maastricht.

Kleijn, R. and Van der Voet, E., Chlorine in Western Europe, a MacTempo Case Study, Materials Accounting as a Tool for Decision Making in Environmental Policy, Centre of Environmental Science (CML), Leiden, April 1998.

Kleijn, R., (2000), Dynamic Substance Flow Analysis: the Delaying Mechanism of the Stocks, with the Case of PVC in Sweden, Ecological Economics, 32, pp.241-254.

Kosson, D.S., Sloot, H.A. van der, Eighmy, T.T., An Approach for Estimation of Contaminant Release During Utilization and Disposal of Municipal Waste Combustion Residues, Journal of Hazardous Material, vol. 47, pp. 43-75, 1996.

Melo, M., Statistical Analysis of Metal Scrap Generation: the Case of Aluminium in Germany, Resources, Conservation and Recycling, Vol. 26, pp 91-113, 1999.

Moore, D. and Tilton, J., Economic Growth and the Demand for Construction Material, Resources Policy, Vol. 22, No. 3, pp 179-205, 1996.

Palm, V., Material Flow analysis in Technosphere and biosphere, Ph.D thesis, 2002.

Rebecca Renner, Sewage sludge Pros and Cons, Environmental Science & Technology, V.34-I.19 1, October 2000.

RIVM, (2001), European Environmental Priorities: an Integrated Economic and Environmental Assessment.

Sakai, S., Sawell, E., Chandler, A.J., Eighmy, T.T., Kosson, D.S., Vehlow, J., Sloot, H.A. van der, Hartlen, J., Hjelmar, O., World Trends in Municipal Solid Waste Management, Waste Management, Vol.16, No. 5/6, pp. 341-350, 1996.

Scoullos, M., G.H. Vonkeman & I. Thornton. EUPHEMET – Towards an integrated EU policy for heavy metals. EC-DG Research, Brussels, Belgium. 2001.

Sloot, H.A. van der., Present Status of Waste Management in the Netherlands, Waste Management, Vol.16, No. 5/6, pp. 375-383, 1996.

Stockhammer, E., Hochreiter, H., Obermayr, B., and Steiner, K., The Index of Sustainable Economic Welfare (ISEW) as an Alternative to GDP in Measuring Economic Welfare. The Results of the Austrian (Revised) ISEW Calculation 1955-1992. Ecological Economics. Vol. 21, P. 19-34, 1997.

Tiltone, J., World Metal Demand – Trends and Prospects, Resources for the Future, Washington D.C., 1990.

Tilton, J.E., More, D., (1996), Economic Growth and the Demand for Construction Material, Resources Policy, 22, 3, pp. 197-205.

Tukker, A., Buijst, H., Oers, L. and Van der Voet, E., Risk to Health and the Environment Related to the Use of Lead in Products, TNO, Delft, The Netherlands, 2001.

Turner, P., (1999), Green Accounting and the Welfare Gap, Ecological Economics, 30, pp.161-175.

Vereniging Van Afvalverwerkers (VVAV), Jaarverslag, 2001.

Voet, E. van der, L. van Egmond, E.G.M. Kleijn & G. Huppes (1994). Cadmium in the European Community - a policy oriented analysis. Waste Management and Research 12, pp 507-526.

Voet, E. van der, Substance From Cradle to Grave: Development of a Methodology for the Analysis of Substance Flows Through the Economy and the Environment of a Region, Ph.D. Thesis, Leiden university, Leiden, 1996.

VROM (2000), Circulaire streefwaarden en interventiewaarden bodem sanering, Nederlandse staatscourant 39, 24-02-2000.

APPENDIX A - GENERAL INFORMATION AND DATA

CONFIDENTIAL

APPENDIX B - DERIVING A MODEL EQUATION FOR DIFFERENT LEAD PRODUCTS

ONLY B.1 IS SHOWN AS AN EXAMPLE, THE MODEL EQUATIONS FOR OTHER LEAD APPLICATIONS ARE LEFT OUT FOR CONFIDENTIALITY REASONS.

For all applications : * significant at 95%, ** significant at 99%

B.1 Deriving a model equation of the inflow of lead sheets (1988-1998)

1- Analysis of the impact of the population growth in the past on the inflow of lead sheets

Inflow = f (PopG*)

Pop* = $a_0 + a_1$. PopG(t) + a_2 . PopG(t-1) + a_3 . PopG(t-2) ....

Variable	Time delay	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
PopG. 88	0	29293 (7.9)	-20058 (-0.5)		0.02	0.3
PopG. 87	1	245232 (6.7)	30681 (0.8)		0.06	0.6
PopG. 86	2	21828 (7.1)	59898 (1.8)		0.27	3.4
PopG. 85	3	29275 (7.1)	-19813 (-0.4)		0.02	0.2
PopG. 84	4	32877 (11.9)	-59306 (-2.0)		0.31	4.1
PopG. 83	5	31890 (14.0)	-51015 (-2.0)		0.31	4.1
PopG. 82*	6	32408 (16.6)	-59057 (-2.6)		0.43	6.9
PopG. 81	7	31217 (13.3)	-45525 (-1.6)		0.23	2.7
PopG. 80	8	26708 (9.6)	8440 (0.2)		0.01	0.1
PopG. 79	9	25181 (9.1)	27019 (0.8)		0.07	0.7
PopG. 78	10	27969 (9.8)	-6805 (-0.2)		0.04	0.1
PopG. 77	11	29124 (10.2)	-21165 (-0.6)		0.04	0.4
PopG. 76	12	2698.8 (9.7)	31947 (0.4)		0.01	0.2
PopG. 75	13	23526 (11.3)	45103 (1.9)		0.29	3.7
PopG. 74**	14	21583 (13.2)	65064 (3.6)		0.60	13.5
PopG. 73*	15	21250 (10.1)	65277 (2.9)		0.49	8.9
Popg. 72	16	22251 (7.4)	50755 (1.7)		0.25	3.1
PopG. 71	17	23517 (7.7)	35439 (1.2)		0.15	1.6
PopG 74,73*	14, 15	20623 (10.7)	46633 (1.7)	27667 (0.9)	0.64	7.2
PopG 82,74*	6, 14	23761 (4.8)	-14621 (-0.4)	54562 (1.9)	0.61	6.3

PopG* = $a_0 + a_1$. PopG(t-14)

PopG* = 21583 + 65064 PopG(t-14)

2- Analysis of the impact of Gross Domestic Product (GDP) in the past on the inflow of lead sheets

Inflow = ƒ (GDP*)

GDP* = $a_0 + a_1$. GDP(t) + a_2 . GDP(t-1) + a_3 . GDP(t-2) ………

Variable	Time delay	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
GDP. 88	0	33302(11.8)	-1.82(-2.1)		0.33	4.5
GDP. 87*	1	33010(13.4)	-1.82(-2.3)		0.37	5.4
GDP. 86*	2	32781(17.2)	-1.84(-2.9)		0.48	8.4
GDP. 85*	3	32089(20.3)	-1.75(-3.1)		0.51	9.4
GDP. 84*	4	31582(20.1)	-1.72(-2.7)		0.45	7.6
GDP. 83*	5	31489(22.0)	-1.82(-2.9)		0.49	8.9
GDP. 82	6	30684(19.4)	-1.57(-2.2)		0.34	4.7
GDP. 81*	7	31102(19.5)	-1.93(-2.4)		0.39	5.8
GDP. 80	8	30915(16.2)	1.94(-1.9)		0.28	3.6
GDP. 79	9	30994(12.6)	-2.11(-1.5)		0.19	2.2
GDP. 78	10	32033(13.0)	13.01(-1.9)		0.29	3.6
GDP. 83,84	5,4	31533(19.6)	-1.66(-0.8)	-0.168(-0.08)	0.49	3.9
GDP. 84,85	4,3	32090(19.1)	0.05(0.0)	-1.809(-0.93)	0.51	4.2
GDP. 85,86	3,2	32348(15.8)	-1.35(0.7)	-0.454(-0.22)	0.51	4.2

GDP* = $a_0 + a_1$. GDP(t-3)

GDP* = 32089 + (-1.757) GDP(t-3)

3- Analysis of the impact of per capita GDP in the past on the inflow of lead sheets

Inflow = ƒ (GDP/C*)

GDP/C* = $a_0 + a_1$. G/C(t) + a_2 . G/C(t-1) + a_3 . G/C(t-2) ………

Variable	Time delay	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
G/C. 88**	0	49039(7.7)	-1.596(-3.4)		0.56	11.5
G/C. 87**	1	50611(8.4)	-1.75(-3.9)		0.62	15.0
G/C. 86*	2	49531(7.2)	-1.702(-3.2)		0.53	10.4
G/C. 85*	3	47399(6.3)	-1.56(-2.6)		0.44	7.1
G/C. 84*	4	45077(5.9)	-1.41(-2.3)		0.37	5.3
G/C. 83*	5	45082(6.4)	-1.44(-2.5)		0.41	6.3
G/C. 82*	6	45606(7.1)	-1.51(-2.8)		0.47	8.1
G/C. 81*	7	47630(7.4)	-1.706(-3.2)		0.52	9.9
G/C. 80*	8	49355(6.2)	-1.88(-2.8)		0.45	7.6
G/C. 79	9	50388(4.3)	-1.99(-1.9)		0.29	3.8
G/C. 78	10	54548(-2.4)	16053(1.4)		0.24	2.8
G/C.88,87*	0,1	50629(8.2)	1.84(0.7)	-3.63(-1.4)	0.64	7.4
G/C.87,86*	1,2	49016(8.0)	-4.24(-1.8)	2.66(1.1)	0.67	8.2
G/C.88,86*	0,2	49600(7.0)	-1.18(-0.7)	-0.47(-0.3)	0.56	5.2

$GDP/C^* = a_0 + a_1 \, . \, GDP/C(t-1)$

$GDP/C^* = 50611 \; - 1.75 \; GDP/C(t-3)$

4- Analysis of the impact of lead price in the past on the inflow of lead sheets

Inflow = ƒ (P*)

$P^* = a_0 + a_1 \, . \, P(t) + a_2 \, . \, P(t-1) + a_3 \, . \, P(t-2)$ ………

Variable	Time delay	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
P. 88	0	29348(6.7)	-4814(-0.4)		0.02	0.2
P. 87*	1	36092(10.8)	-22031(-2.6)		0.43	6.9
P. 86*	2	33347(12.6)	-15966(-2.3)		0.36	5.2
P. 85*	3	32648(15.0)	-15189(-2.5)		0.40	6.1
P. 84	4	31001(12.8)	-10892(-1.5)		0.20	2.3
P. 83	5	29517(12.6)	-6678(-0.9)		0.08	0.8
P. 82	6	28355(12.2)	-3050(-0.4)		0.01	0.2
P. 81	7	29603(13.3)	-7046(-1.0)		0.10	0.1
P.87,86*	1,2	37477(11.3)	-16107(-1.8)	-10000(-1.4)	0.54	4.8
P.86,85	2,3	34249(12.9)	-9041(-1.0)	-10079(-1.3)	0.47	3.6
P.87,85**	1,3	38843(13.7)	-18245(-2.6)	-12301(-2.5)	0.68	8.8

$P^* = a_0 + a_1 \, . \, P(t-1) + a2 \, . \, P(t-3)$

$P^* = 38843 \; - 18245 \; P(t-1) - 12301 \; P(t-3)$

To evaluate the contribution of each price to the change in the inflow of lead sheets:
18245+12301 = 30546
18245/30546 = 0.597 ~ 60%
12301/30546 = 0.402 ~ 40%

$Price_{new} = 0.6*P(t-1) – 0.4*P(t-3)$

This equation includes the affect of the price in two years and will be used in the combined variable analysis in 6.

5- Analysis of the impact of sectoral share in GDP in the past on the inflow of lead sheets

Inflow = ƒ(Construction*)

Cons* = $a_0 + a_1$. Construction(t) + a_2 . Construction(t-1) + a_3 . Construction(t-2) ………

Variable	Time delay	β_0 (t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Cons. 88	0	34231(10.3)	-41.8(-2.1)		0.32	4.3
Cons. 87	1	33543(12.2)	-39.4(-2.3)		0.36	5.1
Cons. 86*	2	33201(17.1)	-39.34(-3.1)		0.51	9.4
Cons.88,87	0,1	34081(9.9)	-12.84(-0.3)	-29.4(-0.7)	0.36	2.3
Cons.87,86	1,2	32427(12.3)	17.869(0.5)	-52.97(-1.6)	0.52	4.3

Cons* = $a_0 + a_1$. Cons(t-2)
Cons* = 33201 – 39.34 Cons(t-2)

6- Analysis of the impact of the combined variables on the inflow of lead sheets

Inflow = ƒ(Population Growth*, Price*, GDP*, GDP/C*, Cons*, Time)

Variable	B_0(t-value)	β_1 (t-value)	β_2 (t-value)	R^2	F-statistics
Price$_{new}$**	38856(14.8)	-30570(-4.4)		0.68	19.8
PopG74**	21583(13.2)	65064 (3.7)		0.60	13.5
GDP85*	32089(20.3)	-1.757(-3.1)		0.51	09.4
GDP/C87**	50611(8.4)	-1.75(-3.9)		0.62	15.0
Cons86*	33201(17.1)	-39.34(-3.1)		0.51	09.4
Time*	29831(32.3)	-403.6(-2.9)		0.49	08.8
Price, PopG	33334(4.9)	-21716(-1.8)	24635(0.9)	0.71	10.1
PopG, GDP	25583(6.8)	45096(1.8)	-0.83(-1.2)	0.65	07.7
Time, GDP				0.51	04.2
Price, Time	37304(12.6)	-23974(-2.6)	-152.93(-1.1)	0.72	10.6
Time, PopG	23956(6.7)	-147(-0.7)	48417(1.7)	0.62	06.7

The following model will be used to calculate the inflow of the lead sheets:

Inflow = 21583 + 65064*Population Growth (t-14)