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

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Summary

The research presented in this thesis is aimed at developing a dynamic substance flow-stock model that can be used to estimate future resource availability, emissions and waste streams. The research follows three consecutive stages:

- The first part develops a dynamic stock model, which combines elements from both physical and economic models, and establishes a link to a flow model, thus creating a dynamic substance flow-stock model.
- The second part develops a software tool able to carry out the dynamic substance flow-stock model.
- The third part implements the model in two case studies relevant to environmental policy. The first case study investigates the environmental and economic consequences of the development of lead stocks in the EU and the Netherlands. The second case study investigates the potential impacts of using platinum in the newly introduced fuel cell technology and addresses issues of both resource availability and environmental impacts.

This thesis consists of 9 chapters. Chapter 1 provides the introduction. Chapters 2 and 3 are dedicated to methodological aspects in substance flow analysis (SFA) and a representation of the dynamic substance flow-stock model. Chapters 4 to 8 include applications of the model in case studies. Chapter 9 is dedicated to a general discussion, conclusions and recommendations of aspects related to the substance flow-stock model and its applications.

Methodology

In chapter 3, the dynamic substance flow-stock model is presented. The first sections of each of the consecutive chapters (chapters 4 to 8) discuss methodological aspects specifically related to the case studies.

General

The model developed and presented in this thesis extends the currently available SFA models in three respects. Firstly, by combining flows and stocks. Secondly, it combines physical and economic elements. And thirdly, it operates at two levels: those of products and substances.

The model includes two subsystems; the economic and the environmental. The economic subsystem includes four processes, (extraction, production, consumption and waste management), several flows and several stocks. The main stocks in the economic subsystem are the stock of the substance in use, the stock of the substance in agricultural soil and the stock of the substance in landfill sites. Although agricultural soil may be regarded as an environmental compartment, it is treated in the model as part of the economic subsystem. Landfill sites are also treated as part of the economic subsystem. The environmental compartments in the model are limited to the air, water and non-agricultural soil. The model treats these environmental compartments as sinks. The environmental flows and stocks that arise as a consequence of economic activities that use the substance are specified in detail. Transboundary environmental flows, in and out of the system are assumed to be equal when the model is applied to national or local systems. It is not necessary to make this assumption when the model is applied at a global level. The main stocks in the environmental subsystems are the stock of the substance in the biosphere and the stock of the substance in non-agricultural soil.

The model uses two approaches to model the stock-in-use, and the flows of substances into (the inflow) and out of (the outflow) the stock-in-use. The first approach starts by taking historical data on the inflow and the product lifetime. The second approach starts by taking historical data on the stock-in-use, the inflow, and the product lifetime. Two approaches are used to model the inflow of substances into the stock-in-use. In the first, the inflow of substances is modelled based on two equations; one describing the inflow of products and the other describing the substance content of products. Each one is determined by different factors. For each product, the inflow into the stock-in-use is modelled based on a regression model that describes the inflow as a function of selected socio-economic variables. The socio-economic variables used in the model are GDP, per capita GDP, sectoral share of GDP, population, and material price. A time variable is used as a proxy of the influence of other variables. Some of the variables in the model are exogenous (GDP and population) and others are endogenous (price). The substance content of products is treated either as constant or changing overtime. It is modelled either as a function of time or by using the learning curve concept. The learning curve concept, which introduces endogenous technical change into the dynamic model, is adapted to model the substance content as a function of the cumulative production. In the second approach, the inflow of the substance into the stock-in-use is modelled directly by one equation using different types of models (linear model, log-log model and the intensity-of-use technique). This approach is used when the data on the substance level (the total amount of the substance used in certain products) is directly available. In this case, the explanatory variables used in the model cover both the product inflow and substance content. Although the first approach has several advantages, sometimes the second approach is necessary as, most data sources directly provide the consumption of substances. The outflow is based mainly on the physical mechanisms of leaching and delay. The leaching model estimates the outflow out of the stock-in-use due to emissions during use, through corrosion, evaporation and suchlike, expressing this as a fraction of the stock-in-use. The emission factors may change over time and are determined by a wide range of factors, such as the surrounding atmosphere, the weather, maintenance, and others. The delay model estimates the discarded outflow as a delayed inflow with a certain life span. The product life span is never exactly known, however it can take an average value or be assumed to fit a Weibull distribution based on available information. Other distributions are possible. In extreme situations - for example a very long life span, or a very wide, narrow or skewed distribution - this may considerably influence the results.

The geological stock of a substance is treated as the economic stock. The model takes the geological stock of substances as including the currently known reserve and identified resources. Depending on the initial stock in the model, additions (inflows) to the resource stock can include newly found ores, or existing ores that become profitable. The extracted flow (the outflow from the resource stock) is mainly determined by the demand for the substance and the availability of secondary materials. The mechanisms through which the impacts of price increases and the development of new technologies may influence a possible increase in the resource stock (by making the currently known resource stock more profitable or low-grade resources possible to be extracted) are not included in the model. These known resources are already included in the identified resources. The possibility of finding new ores, which might increase the availability of resources, is not included in the model.

The stock of the substance stock in landfill sites is determined by the inflow of the substance into landfill sites and the leaching outflow from them. The inflow of the substance to landfill sites originates from different parts of the economic subsystem and the leaching outflow is determined by the substance characteristics and landfill technology.

The stock of the substance in agricultural soil is mainly determined by flows into and out of agricultural soil. Flows into agricultural soil are mainly from atmospheric deposition, the use of fertilizers, and the use of sewage sludge and manure. The outflow is mainly determined by the uptake rate of food and fodder.

As with substance flow analysis, the substance flow-stock model can be applied at different levels: international, national, and local. If the modelled system is small (national or local), disconnections will exist between the different compartments of the economic subsystem (extraction, production, consumption, and waste management) as a result of trade (the import and export of the refined substance, of products containing the substance and of obsolete products.). The smaller the country, the stronger this disconnection will be. This disconnection does not exist when the model is applied at the global level. The dynamic substance flow-stock model presented in this thesis treats the import and export of products, obsolete products and refined substances as a net import, which is estimated as a balancing item.

Lead case study

The model includes flows and stocks of lead in the economic subsystem and the environmental flows and stocks that are directly linked to economic activities. The model includes the most significant intentional applications of lead, such as batteries, lead sheet, cathode ray tubes and cable sheathing. It also includes non-intentional applications of lead, such as the utilization of secondary flows (fly and bottom ash) in road construction material, building materials and agricultural soil. These applications are assumed to be sufficient to estimate the waste streams and emissions of lead. Transboundary flows of lead and other flows and stocks that result from the loops and cycles within the environmental subsystem itself are not been treated in detail.

In modelling the inflow, outflow and stock of lead in use for lead applications, the first approach, that starts from the historical data on the inflow and the products' life span is adopted. The one exception to this is that of cathode ray tubes, for which the flows and stocks are modelled based on the second approach. The inflow of lead into the stock-in-use of its different applications is modelled based on the substance/product approach, with the explanatory variables (GDP, per head GDP, population, and time) being exogenously determined. These variables appeared to be sufficiently explaining a number of past trends of these flows, such as the inflow of lead to the consumption phase, the production of refined lead, the production of other heavy metals and the production of oil and its use in electricity production. Howver they appeared insufficient in describing the past trend of the inflow of phosphate fertilizers and the production of electricity from coal. Therefore, in modelling these flows time is used as a proxy of the effect of other influential variables. In the case of fertilizers, other explanatory variables, such as the number of animals and the agricultural yield could also have been used in the analysis. However, these variables have not been used in the Dutch case, as it is clear that the most influential variables are related to policy. Therefore, the future use of fertilizer is estimated using time as the explanatory variable as this captures the impact of policy. A minimum value on the use of fertilizers is set in the model based on a scenario developed by RIVM. The past use of coal for electricity production could not be directly explained by the explanatory variables, but they were sufficient to describe total electricity production and production of electricity from other sources. Therefore, it was possible to estimate the production of electricity from coal as a balancing variable. The discarded outflow of lead applications is modelled using data on past inflows and specific life spans, which are assumed to fit a Weibull distribution.

Imports and exports at different stages in the economic subsystem are treated as a net import which is estimated as a balancing item of the two different compartments.

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

Platinum case study

The model focuses mainly on the economic subsystem and includes the extraction and production of Pt (from both primary and secondary resources), and the production, consumption and waste management of applications containing Pt. These include fuel cells, catalytic converters, and other uses in the chemical, electrical and electronic, glass and petroleum industries, investment, jewellery and other applications. The model also includes the production of co-produced metals (Ni and Cu) from Pt primary resources, the consumption and waste management of Ni and Cu applications and the production of Ni and Cu from secondary resources. The model includes emissions to the environment and the resource stock in the environment.

The demand for Pt is looked at globally and supply comes from four sources (The Republic of South Africa, Russia, the USA and Canada, and other countries). Pt ores are identified as Platinum Group Elements (PGE) dominants ores, Ni-Cu dominant ores and miscellaneous ores, depending on the geographical distribution. Pt resources in these ores are classified as current reserve and identified resources.

The model consists of a set of differential equations describing the change of the magnitude of the stock of Pt in the system's compartments over time. There is assumed to be no change in the magnitude of the economic stock of the substance over time in relation to the production processes, the collection processes, and the recycling processes of Pt applications, and in the Pt market (i.e. the input is equal to the output). The changes of the magnitude of the stock of Pt in use and the resource stock of Pt over time are determined by the inputs into and the outputs from these stocks. In addition,, the model consists of several model relations describing the inflow of substances into the stock-in-use as functions of the socio-economic variables.

The inflow and outflow of Pt and the stock of Pt in use in all Pt applications are modelled based on the first approach that starts from historical data on the inflow and the products' life spans. The main driving force in the model is the global demand for Pt. This is estimated from the demand for its applications (Fuel Cells (FC), Catalytic Converters (CC), and other applications) and the amount of Pt required for each application. The inflow of Pt into the stock-in-use of FC and CC is modelled using the substance/product approach. The inflow of Pt into the stock-in-use of other applications is modelled using the substance approach. The demand for Pt applications is modelled based on socio-economic variables such GDP, per capita GDP, population size, and material price. Some of the explanatory variables, such as GDP and population, are exogenously determined and others, such as the price and technological development, are endogenously determined. Different scenarios for FC market penetration are used to estimate the demand for FC and the replacement of CC. The Pt required for each application is modelled as a function of accumulated production using the learning curve. Scenarios used for the market penetration of FC and the progress ratios used in the learning curve have a great impact on the model outcome. Several other factors are important in determining the model outcome. These include the life span of the applications, the collection rates of the discarded applications and the efficiency of production processes (primary and secondary). The discarded outflow of Pt applications is modelled from the past inflow and a specific life span, which is taken as an average value.

The initial stock in the use phase is assumed to be zero. This assumption will not have any impact on the model outcome in terms of resource availability. However, it will lead to an underestimation of the magnitude of the stock in the use phase. The initial resource stock in the biosphere has been given two values. The first is the value of the current reserve and the second is the value of identified resources.

An analysis is carried out to examine the sensitivity of the model outcome to the parameters in the model.

Case studies

Lead

The first case study, of lead, is presented in chapters 4 to 7. These chapters describe the modelling aspects, present the data, and analyse the long-term management of the intentional and non-intentional use of lead. The lead case study is mainly aimed at:

- evaluating the economic and environmental consequences of the developments of lead stocks on the long-term management of lead;
- evaluating the long-term direct environmental consequences of non-intentional flows of lead and compare them to those of its intentional flows and;
- evaluating the long-term environmental and economic consequences of non-intentional existence of lead in applications.

The main outcome of the model suggests that in the Netherlands the amount of lead available for recycling is expected to exceed the demand for lead in the near future. This model however, is restricted to one country and more general conclusion about lead availability and demand would require an analysis on a larger scale (regional or global) where imports and exports would play a lesser role. If comparable developments can be detected on a larger scale as well, this finding may have consequences for the future management of lead. It would suggest that the demand for lead is dropping as a result of policies designed to phase out its use. On the other hand, the supply from secondary sources is increasing as a result of the past build up of stocks in society. Moreover, the supply from primary sources continues and is expected to continue for reasons other than meeting new demand for lead. All this may have consequences for the price of lead, for the profitability of primary production and the recycling industry. As a result the landfill and incineration streams might increase at the expense of recycling, and ultimately may lead to an increase in emissions. The model also suggests that the environmental consequences of the non-intentional use of lead from zinc and iron ores and from coal are more severe than those originating from the waste streams of the intentional applications of lead. The amount of lead generated by non-intentional sources is sufficient to provide at least part of the total demand for lead. Therefore, special attention should be given to managing these non-intentional flows of lead, especially those originating from mixed primary resources containing lead as a contaminant (zinc and iron ores and coal). In addition, recovery of the available lead in secondary materials, such as fly and bottom ashes generated from coal fired power plants and waste incineration plants prior to landfilling or use as construction materials is recommended. The residues of production and consumption of non-intentional applications of lead can be seen as potential sources for lead, and other metals, in the future.

Platinum

The second case study is presented in chapter 8 and concerns the use of platinum in the newly introduced fuel cell technology. This case study aims at:

- investigating the potential long-term impact of the increased use of platinum in fuel cell technology and other applications in terms of future resource availability and;
- evaluating the long-term consequences of the increased demand for platinum on the cycles of other co-produced metals, especially Ni and Cu

The model shows that the main losses of platinum occur in the waste management of fuel cells and catalytic converters and the production of platinum from primary sources. The main outcome of the model suggests that current reserves and identified resources of platinum will be depleted before the end of the century if no additional measures are taken. However, the model also suggests that there some factors on the demand and supply sides may extend the availability of platinum over time. These include: the increasing efficiency of fuel cell production, the market penetration of fuel cells, together with the increasing efficiency of the waste management of fuel cells and catalytic converters, the increasing efficiency of the production of platinum from primary sources, and the increasing life span of fuel cells. Technological developments in fuel cell production can play an important role in increasing the availability of platinum, as can improvements in mining technologies. Moreover, it is recommended that fuel cell technology be gradually introduced to the market and to investigate the possibility of finding other sources of supply of platinum. Platinum has been accumulating in the soil since the introduction of catalytic converters and this could represent a potential source of platinum in the future. Other sources include mixed primary resources.

The model also shows that the metals co-produced with platinum (Cu and Ni) will be affected by the increased production of platinum. The possibility of an oversupply of these co-produced materials might have consequences in terms of their secondary production and their primary production from other sources.

The outcome of the model suggests this will not have major consequences that for the copper cycle as the demand for copper is very high compared to the supply from this source. For nickel, the story is different as the supply of this metal from platinum ores is expected to exceed its demand, which will have profound consequences for both the primary mining and the recycling of nickel.

General discussion, conclusions and recommendations

Chapter 9 provides a general discussion, with conclusions and recommendations of aspects related to the substance flow-stock model and its application in the case studies.

In the first part of chapter 9, a number of issues related to the dynamic flow-stock model are discussed. These mostly pertain aspects relating to the combination of flows and stocks, the combination of physical and economic elements, the level of scale in modelling substance flow and stocks, the inclusion of the economic and environmental subsystems, operating at the levels of products and substances and the role of uncertainty. It is recommended that a substance flow-stock model should include both economic and physical-chemical variables as substance flows through the economy are basically determined by the economic demand for substance-containing applications. In turn, substance flows out of the economy in the shape of waste and emissions are primarily determined by the physical-chemical properties of the substance. It is also recommended to include different factors or explanatory variables that cover different economic driving forces: the demand for products containing the substance, the demand for secondary materials and policies on waste. It also recommends using the product/substance approach and learning curve concept to model the flow of substances into the stock-in-use and the substance content of products.

Recommendations for further development

Some interesting subjects for future research in the area of dynamic substance flow analysis are: the inclusion of trade in national dynamic substance flow-stock models, the inclusion of the mechanisms describing the impacts of price and technology development on the resource stock in the biosphere and the inclusion of the impacts of energy use in the mining processes in global dynamic substance flow-stock models. Worthwhile opportunities also exist to investigate the possibilities of linking the dynamic substance flow-stock model to other environmental models, such as environmental fate models and environmental risk assessment models. This could improve estimates of the environmental concentration of substances in environmental media and enhance assessment of the risks entailed.