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

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Chapter 9 Discussion, Conclusions and Recommendations

9.1 General discussion and evaluation of the case studies

The model developed and presented in this thesis is a dynamic substance flow-stock model that can be used to estimate future resource availability, emissions and waste streams. The model is extends the currently available SFA models, firstly by combining flows and stocks, secondly by combining physical and economic elements, and thirdly by operating at two levels: of products, and substances.

This concluding chapter develops the discussion of a number of issues that were raised in chapters one to three of this thesis. These particularly pertain to a. the combination of flows and stocks, b. the combination of physical and economic elements, c. the level of scale in modelling substance flow and stocks, d. the inclusion of both the economic and the environmental subsystems, e. operating at two levels: products and substances and f. the role of uncertainty in dynamic substance flow-stock model.

In relation to the issue of the combination of flows and stocks, chapters one and two stated that several types of analysis are used to describe the relations between flows and stocks in the economic subsystem, including accounting and static and dynamic modelling (Van der Voet, 1996). The main difference between static and dynamic models is that the latter includes stocks within society (Bergbäck & Lohm, 1997), which play an important role in determining future waste and emissions of many hazardous substances to the environment and enable us to take into account the impact of delay, especially for applications with a long life span. Although the attention of those in the SFA community has been mainly focused on drawing up accounts and on comparative static modelling (Bringezu et al., 1997 and Bauer et al., 1997), a few specific substance stock databases or models have recently been published (Baccini, et al., 1996, Zeltner, et al., 1999, Kleijn, et al., 2000, Binder, 2001, Van der Voet, et al., 2002, Ayres, et al., 2003, Müller, et al., 2004, Spatari,et al., 2005, Binder et al., 2006). The model developed and presented in this thesis is a dynamic substance flow-stock model that consists of several sub-models. Each one consists of several substance flows and, in some cases, one or more stocks. In the chosen setup, the flows and stocks mutually influence each other: stocks are the result of flows while, at the same time, some of the flows are a result of the stocks. The main stock in the model is the stock-in-use. As stated in chapter 2, two different approaches can be used to model the stock-in-use, the inflow of substances into, and the outflow of substances from, the stock-in-use. The first approach starts from historical data on inflows and the product lifetime. The second approach starts from historic stock-in-use and the product lifetime. Although the first approach is the main one used in the model presented in this thesis, the second approach is also used, especially when statistical data on the inflow is lacking or where no correlation between the inflow and the socio-economic variables could be found. In general, the first approach leads to better estimates of the outflow of substances from the stock-in-use. This is mostly because the first approach directly estimates the outflow from the inflow, which is measurable. By contrast in the second approach, the outflow is calculated from an estimated stock. Other stocks of substances in the system also exist in the biosphere. For example, the geological stock which can be treated as the economic stock. The geological stock of substances used in the model (e.g. for platinum) includes both the currently known reserve and identified resources. Depending on the initial level of stock used in the model, the addition (inflow) 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 model does not contain mechanisms that describe the possible impacts of price increases or the development of new technologies in increasing the resource stock through making the currently known resource stock more profitable or making it feasible to extract lower-grade resources. However, these known (but unprofitable) resources are already included in the identified resources. The model also does not take into account the possibility of finding new ores, which might positively affect future resource availability. Future research may well focus on these issues.

With regard to the second point, of combining physical and economic elements into one model, chapter 2 stated that economic models usually ignore some crucial mechanisms, such as the physical laws of mass balance and stock building over time, that underlie the generation of waste and emissions (Van der Voet and Kleijn, 2000). On the other hand, material flow models limit themselves to physical considerations and do not include costs or incorporate mechanisms of economic analysis. The dynamic substance flow-stock model developed here is the first model in the field of substance and material flow analysis to combine elements from both types of models. In so doing the limitations of existing economic and material flow models can be overcome and their strengths combined. The inclusion of economic elements in substance flow models enables coverage of a wide range of factors that affect the dynamic behaviour of the system, particularly in explaining the demand for products and, consequently, the demand for substances. The dynamics of the inflow and outflow of the substance in different phases of the economic subsystem are determined by distinct driving forces, implying the need to employ different explanatory variables in these sub-models. The socio-economic variables used in the model are: GDP, per capita GDP, sectoral share in GDP, population and material price. A time variable is used as a proxy for other determining factors. For lead, these variables were sufficient to explain a number of past trends in both intentional and non-intentional flows (R^2 was between 0.34 and 0.95). However, the model forecasts are only valid assuming no unpredicted changes, such as the development of a completely new substitute. Although these explanatory variables proved to be the most influential ones other, more case-specific, variables could be also included in the analysis, subject to the availability of historic data and projections of the future development of these variables. For lead, the adopted explanatory variables did not appear to adequately describe a number of products, such as the flow of phosphate fertilisers and electricity production from coal. In modelling these flows time was used as a proxy of the effect of other influential variables. In the case of fertilisers other case-specific explanatory variables, such as the number of animals and agricultural yields, could also have been used in the analysis. However, these variables were not used in the Dutch case, as it is clear that the policy context is one of, if not the, most influential variables. Although the past use of coal for electricity production could not be directly explained by the explanatory variables, they were sufficient to describe total electricity production and the production of electricity from other sources and it was possible to use the production of electricity from coal as a balancing variable. Other general variables such as the general consumer price index (CPI) and the CPI for specific products could also have been used. This would have been especially useful in the absence of specific price information.

In relation to the third point, the level of scale in modelling substance flow and stocks, chapter 2 noted that substance flow analysis can be carried out at different levels: international, national, and local. The main issue regarding the level of scale is related to inclusion of economic elements in the model. If the modelled system is small (national or local), the components of the economic subsystem (extraction, production, consumption, and waste management) may be disconnected by trade (imports and exports of the refined substance, products containing the substance and obsolete products.). The smaller the country is, the stronger the disconnection will be. This disconnection does not exist if the system is modelled at the global level. In static substance flow analysis, it is sufficient to know the amount of imports and exports. However, in the dynamic substance flow analysis, knowing the amount of the imports and exports, or a time series of both, still requires the need to estimate both in the future and to arrive at an analysis of trade, using different explanatory variables. Most of the dynamic SFA models developed so far are either carried out on a global level (so imports and exports are not an issue) or do not take imports and exports into account, as in the model developed for copper in the USA (Zeltner et al. 1999). In the dynamic substance flow-stock model presented in this thesis, the import and export of products, obsolete products and refined substances are taken into account and treated as net imports that are estimated as a balancing item between two different components. This implies that information on past imports and exports are needed. For the future imports and exports are estimated together as one amount that its value could be positive or negative. It is not possible however to separate imports and exports and no analysis of trade can be made. This can be an issue for further research. This is the case for the lead model. Imports and exports at different stages in the economic subsystem of lead are treated as net imports to be estimated as a balancing item between two different components. This assumption is not needed in global models, such as the platinum case study in this thesis.

Regarding the forth point, the inclusion of the economic and environmental subsystems, chapter 3 stated that the system in SFA is treated as a physical entity that consists of two subsystems, the economic and the environmental. However, sometimes, it is not clear where exactly to draw the border between the two. In the developed substance flow-stock models the economic subsystem includes extraction, production, consumption and waste management and the environmental components are restricted to air, water and non-agricultural soil. Agricultural soil may be seen as an environmental compartment, although the model treats it as part of the economic subsystem, as it is used as a means of production. Landfill sites are also treated as part of the economic subsystem, since in the Netherlands, at least, they are generally under human management. The choice of treating a landfill or agricultural soil as part of the environment or of the economy does not make any difference in modelling terms or in the outcome of the SFA model. This is in contrast to, for example, LCA where the boundary between the technical subsystem and the environment has to be drawn as one of the system boundaries (Guinée et al., 1993) as this determines the classification of "emissions". It is generally accepted that emissions from landfill sites should be included in the inventory and therefore, that landfill sites should be included in the technical subsystem (Heijungs et al., 1992 and Finnveden et al., 1995).

In most SFA studies the focus has been more on the economic subsystem (Zeltner et al., 1999, Graedel et al., 2002, Spatari et al., 2005), however some studies have placed more emphasis on the environmental subsystem (van der Voet, 1996, Guinee et al., 1999, Palm, 2002 and Tangsubkul et al., 2005). In principal, the level of detail required in including the environmental subsystem depends on the questions to be answered. Lead model includes detailed information about lead flows and stocks in the economic subsystem and environmental flows and stocks, which are directly linked to economic activities. The environmental components are generally treated as sinks (i.e. stocks with inflow but no outflow). Loops and cycles within the environmental subsystem are not included in detail. This level of detail is considered to be sufficient for estimating waste streams and emissions. The platinum model mainly focuses on the economic subsystem and includes the resource stock in the environment, which is sufficient to answer questions related to resource availability and the impact on the cycles of other metals.

To build a whole picture of the environmental flows and stocks and to analyse the potential risk that substances might cause, it is necessary to include environmental flows and stocks in detail. Future research may well focus on the detailed inclusion of the environmental subsystem and investigate the possibility of linking the flow-stock model with environmental models, such as environmental fate models and environmental risk assessment models.

In relation to the fifth point, operating at two levels (products and substances), chapter 3 stated that a stock of a substance or material is composed of all the products that contain the substance or material. This could include a large number of products, with greatly differing properties and behaviour. This implies that a substance stock model should contain at least two layers: the substance level and the product level. As stated in chapter 3, two approaches were used to model the inflow of substances into the stock-in-use. In the first approach (focused on products/substances), the inflow of substances is modelled on two equations; one describing the inflow of products and the other describing their substance content. Each one is determined by different factors. The inflow of products is determined by the socio-economic variables and the substance content is modelled either as a function of time or by using the learning curve concept, which introduces endogenous technical change into the model. Distinctions between these two levels have also been made in other system dynamic models (Meadows et al., 1972). In the second approach (focusing on substances), the inflow of substances into the stock-in-use is modelled directly by one equation, using different types of models. This approach is used when direct data is available about the substance level (i.e. the total amount of the substance used in the production of certain products). In this case, the explanatory variables used cover both the product inflow and substance content. The same approach has been used in modelling the demand for metals by using the Intensity of Use Technique (Tilton, 1990).

Operating at these two levels enables one to overcome the difficulties of modelling the substance stock-in-use. Often it is not possible to directly model this, because it consists of a large number of applications, each with different behaviour within the economic subsystem. Moreover, the approach also enables the inclusion of developments relating to both products and to substances and materials. Although the first approach has several advantages, the second approach is sometimes necessary as most data sources give direct information about the consumption of substances.

The general stock model, like many environmental or economic models contains several sources of uncertainty, of which three main types can be identified; disturbance (mainly arising from uncertainties in model inputs), perturbation (related to uncertainties about parameters in the model) and unknowable future inputs. In the dynamic substance flow-stock model there are several sources of uncertainty. The explanatory variables used in the model may be incomplete. Some variables may lose importance over time, while others may become more important. The approach used to estimate known flows and some of the parameters in the model's relations have been widely used in environmental and economic research. This approach has both advantages and limitations. The main limitation is future uncertainty. There is a basic assumption that the future relationship between the known flows and the socio-economic variables will be the same as it has been in the past. This is not always the case, as new developments may change

this relationship, such as the development of new materials or processes of production, use and waste management. Moreover, policy may also affect and change this relationship. The leaching model may contain uncertainties in the estimate of the annual loss fraction, which depend on many factors, such as the surrounding atmosphere, the weather, maintenance, and s on. In the delay model, the life span is always taken either as an average life span or as a life span distributed in time. The estimate of the former may be incorrect or liable to change over time. The chosen life span distribution or estimates for the minimum and maximum life span may also be inaccurate. Another possible source of uncertainty lies in the possibility of inaccurate estimates of the initial stocks.
Sensitivity analysis can be used in some of these parameters to evaluate the impact of possible changes on the model's outcome. Others, such as the initial stock of substances, will have a limited impact on the model's outcome. In the case of lead, the difference between the starting year of the past inflow and the starting year of future calculations exceeds the application's life span. For platinum, assumptions about the initial stock will not have any impact on the resource stock but may lead to an underestimate of the magnitude of the economic stock. In future research, comprehensive analysis of uncertainty is recommended.

9.2 Conclusions

9.2.1 Methodology

1. In order to estimate and compare the sources of problematic environmental flows, substance flow-stock model need to include both intentional and non-intentional applications of substances.

2. A substance flow-stock model should include both economic and physical-chemical variables. This is because substance flows through the economy are basically determined by economic demand for substance applications. Thus, in order to model them, the materials in which the substance occurs should be central modelling issue. 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.

3. A substance flow-stock model should include different factors or explanatory variables to cover different economic driving forces, such as the demand for the products containing the substance, the demand for secondary materials and policies on waste.

4. The use of the product/substance approach together with the use of the learning curve concept, which introduces endogenous technical change into the dynamic model of the substance content of products, will lead to better estimates of the demand for substances. Moreover, the inclusion of the stock-in-use and the hibernating stock will give better estimates of emissions and waste flows.

5. A substance flow-stock model can be used to evaluate the economic and environmental consequences of the presence of contaminants in products, by specifying the contribution of different applications to landfill or diffuse emissions over time. This is useful information for policies designed to prevent waste and pollution.

6. A substance flow-stock model can be used to improve the management of resources. It can do so by estimating the future availability of a substance for recycling, the future availability of primary resources and the future demand of the substance and substance containing applications. This is useful information for resource policy.

7. A substance flow-stock model can be used to evaluate technologies intended to promote sustainable production and consumption, at an early stage of their development.

9.2.2 Lead case study

8. The flows of lead through the economy are essentially determined by economic demand for its applications. Thus, the demand for lead can be modelled directly based on socio-economic variables, which appeared adequate in describing the historic demand for lead. This approach is only valid for future extrapolations if we assume that no unpredicted changes will occur.

9. The outflow of lead in the shape of solid waste and emissions is primarily determined by the physical-chemical properties of the substance. The main determinant factors are the life span of products, which are assumed to fit a Weibull distribution, and the emission factors.

10. The outcome of the model suggests that the amount of lead available for recycling in the Netherlands is expected to increase more than the demand for lead in the near future. This means that the demand for lead in the Netherlands can be met through the supply of secondary lead only. If comparable situations exist in other countries this may well have important consequences for the price of lead, on the profitability of primary production and the recycling industry. This might lead to an increase of landfilling and incineration at the expense of recycling, and thus to an increase of Pb emissions.

11. The environmental consequences of the non-intentional use of lead as part of zinc and iron ores and of coal are more severe than those originating from the waste streams of the intentional applications of lead and are considerable compared to those of lead intentional use. Non-intentional inflows of lead constitute less than 10% of the total lead inflow to the economy, but atmospheric emissions of lead from non-intentional applications are equal those from the intentional applications. Non-intentional flows of lead currently contribute 75% of the total amount of lead going to landfill and these are expected to rise to almost 90% of the total in the future.

12. It is expected that non-intentional flows of lead originating from the waste streams of intentional applications will decrease over time, due to more effective recycling. However, the overall flows of lead, as a contaminant in mixed primary resources, appear to be increasing.

13. The amount of lead from non-intentional sources is in principle sufficient to cover more than 10% of the total demand for lead. Therefore, the residues of production and consumption of non-intentional applications of lead can provide potential sources of lead, and other metals, in the future.

14. In terms of metals, the policy of increasing incineration of sewage sludge to minimise the amount of sludge going onto the land or being landfilled, will not be effective if the residues of incineration continue to be partly landfilled without the metals being removed..

9.2.3 Platinum case study

15. The use of a product/substance approach for fuel cells and catalytic converters, which constitute the biggest application of platinum, together with the use of the learning curve concept, which introduces endogenous technical change, combined with using the price as an endogenous variable would give better estimates of platinum demand.

16. The inclusion of the waste management phase of catalytic converters and other applications (in the chemical, electrical, electronic, glass and petroleum industries) in the platinum model would give better estimates of waste flows and help identify the main processes where improvements are needed.

17. Current reserves and identified resources of platinum will be depleted before the end of the century if no additional measures are taken.

18. There are a few factors on the demand and supply sides that may extend the availability of platinum, such as the increasing efficiency of fuel cell production, increases in the life span of fuel cells, their market penetration, increased efficiency in the waste management of fuel cells and catalytic converters and increasing efficiency of platinum production from primary sources.

19. If the fuel cell system is introduced gradually and the efficiency of production and waste management increases (efficiency of production increasing by 2% per year and losses decreasing by 5% per year) and there is an increase in the efficiency of the waste management of catalytic converters (dismantling process efficiency increasing by 30% per year), this will lead to an increase in the availability of platinum by13 years.

20. The main losses of platinum are due to the waste management of fuel cells and of catalytic converters and to production of platinum from primary sources. At current rates of loss the accumulated platinum losses in waste stocks will constitute about 43% of identified platinum resources at the time platinum resources will be depleted.

21. Although the parameters in the model influence the assessment of the availability of platinum, this effect is limited. This is mainly due to the growing demand for platinum, which is mainly driven by demand for fuel cells. This in turn is driven by the demand for vehicles that increases in line with GDP.

22. The metals that are co-produced with platinum will be affected by increased platinum production, which will lead to an increase in the production of co-produced metals. The possibility of oversupply of the co-produced materials might have consequences in terms of their secondary production and their primary production from other sources. This will not have major consequences for the copper cycle as copper demand is much higher than the supply from this specific source. For nickel, however the story is different; as the supply of this metal from platinum ores is expected to exceed its demand, this will have profound consequences for both the primary mining and recycling of nickel.

9.3 Recommendations

9.3.1 Methodological recommendations

1. For forecasting purposes, existing substance flow models should be enlarged to substance flow-stock models in order to overcome the current limitation of forecasting models that are used to estimate solid waste flows and emissions, which are directly proportionate to the economic stock.

2. It is recommended that substance flow-stock models use different explanatory economic variables to cover the different driving forces. The use of more case specific explanatory variables, such as those mentioned for fertiliser flows in the lead case study, is also recommended.

3. It is recommended to study the development of stocks and flows of metals that occur naturally together in the same ores, as policies aimed at a specific metal could effect the cycles of other metals.

4. The development of user-friendly software that builds on the model developed for this thesis using MATLAB and SIMULINK is recommended.

9.3.2 Technical and policy recommendations

1. Special attention should be given to the management of the non-intentional flows of lead, especially those originating from mixed primary resources containing lead as a contaminant (zinc and iron ores and coal).

2. It is recommended to recover the available metals contained in secondary materials, such as fly and bottom ashes generated from coal fired power plants and waste incineration plants, before landfilling or utilising them as construction materials. The removal of metals from residues generated by the incineration of sewage sludge is also recommended.

3. To increase the availability of platinum, it is important to focus on technology development in the area of fuel cell production. It is also important improve mining technologies to reduce the high losses in the production of platinum from primary resources. Moreover, a gradual introduction of fuel cell technology to the market is also recommended.

4. It is recommended to investigate the possibility of finding other sources of platinum supply. Platinum has been accumulating in the soil since the time that catalytic converters were first used. This could be a potential future source for platinum. Other sources include mixed primary resources.

5. In the long term, it is recommended to not use platinum for new purposes and to look for alternative technologies.

9.3.3 Specific recommendations for further research

1. For future research, it is recommended to focus on the use of the substance flow-stock model in specific case studies related to the area of applications (waste prevention policy, pollution prevention policy, resource policy and technology assessment). Phosphorus is considered a scarce resource and is also a major cause of eutrophication, thus phosphorus management would make a good subject for a dynamic substance flow-stock model with useful implications for pollution and resource policy. Other possible case studies are the assessment of the impacts of the use of indium in solar cells, and electrical and electronic equipment waste (WEEE) management.

2. A further interesting topic for future research is the inclusion of mechanisms to describe the impact of price and technology development on the resource stock in the biosphere and the inclusion of an analysis of the impacts of energy use in the mining processes in the substance flow-stock model.

3. There are opportunities for enlarging the substance flow-stock model to include environmental flows in detail. This would improve estimates of the environmental concentration of substances in environmental media and assessment of their risks. In this respect it is important to investigate the possibilities of linking the substance flow-stock model to other environmental models, such as environmental fate models and environmental risk assessment models.

4. An interesting subject for future research is the inclusion of an analysis of trade in national substance flow-stock models.

5. To model the demand for substances, an approach based on modelling the inflow of substances into the stock-in-use as a function of the socio-economic variables is defined. A second possible approach could be based on estimating the inflow on basis of the substance's economic characteristics, that is, the functions that the substance fulfils in the products in which it is used. These economic characteristics strongly relate to the physical and chemical properties of the substance, which determine aspects such as durability, hardness, resistance to corrosion, protectiveness against radiation, flexibility, colour etc. These characteristics determine whether, or by which material, the substance in question can be replaced. This approach would enable the inclusion of substitution and technical developments in the model in addition to the already included socio-economic variables and remains an interesting issue for further future exploration.

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