# Dynamic Substance Flow Analysis: the delaying mechanism of stocks, with the case of PVC in Sweden.

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**Abstract**
Today's stocks are tomorrow's emissions and waste flows. Due to the time lag introduced by the buffering function of the stock of materials and products in society a environmental problemflows which seem to be under control can easely rebound. In this paper an example is given of how signal processing can be used in dynamic Substance Flow Analysis for estimating the future generation of waste and emissions from present societal stocks. An approach is outlined to estimate the outflow of waste products from stocks on the basis of assumptions on the shape of the curve describing the inflow of new products, the average life span of the products, and the life span distribution. It was found that the chosen shape of the input curve has the most influence on the predicted outflows, especially in the case of possible fashion-type (exponentially increasing) markets. The choice of the shape of the inflow curve could therefore be based on qualitative knowledge of the market of the different products. The life span distribution appears to have a more subtle influence on the height of the peaks and the time that they occur. So far only a normal distribution has been considered; more research is recommended into other types of distribution.

**Key words**
Industrial Metabolism, Signal processing, Substance Flow Analysis, Stocks, Dynamic modeling, PVC

## 1. Introduction

Many of the environmental problems we are facing today are a result of society's processing of materials. One of the challenges of economics is to relate the generation of waste and emissions to societal developments. This can be approached from many sides. One possibility is to look at the societal system in environmental terms. This approach is taken by Ayres (1989) in his introduction of the concept of *industrial metabolism*. This concept argues the analogy between the economy and environment on a material level: the economy's "metabolism" in terms of materials mobilisation, use and excretion to create "technomass" is compared to the use of materials in the biosphere to create biomass. Whereas the biosphere has had billions of years to evolve and attune its processes to such a state that waste generated in one process is converted into a resource for another, the economy is still in its early stages of wastefulness. In order to speed up 'economic evolution', society must look to the biosphere for guiding principles. The description of the economy thus is limited to a description of the physical economy. The research area of *industrial ecology* (Jelinski et al., 1992) occupies itself among others with elaborating and operationalizing this concept, and takes the physical economy as its primary subject.

An important research instrument in this field is the *materials balance*, a tool for describing the materials regime of the economy based on the Law of Mass

Preservation, analogous to the long-standing practice of investigating ecological materials cycles. Analytical tools based on the materials balance are *Materials Flow Analysis* (MFA) and *Substance Flow Analysis* (SFA). These tools are useful for supporting environmental policy (Bringezu et al., 1997): they enable policy makers to trace the origins of pollution problems and to evaluate the appropriateness of the societal management of materials and substances.

Until recently, MFA has concentrated mostly on flows. During the past few years, MFA researchers have realized that stocks may be equally or sometimes even more important. One of the environmental issues where stocks play an important role in SFA is in the prediction of future emissions and waste flows of products with a long life span. In some way or another information on the societal stocks of PVC is needed to supply policy makers with information about future outflows: *today's stocks are tomorrow's emissions and waste flows*. In some studies the magnitude of the anthropospheric stocks has even been the primary focus of the study (e.g. Bergbäck & Lohm 1997 and Patel, 1997). These exercises have established the importance of considering stocks. Large stocks have accumulated in the societal system which must be dealt with in some way or other (Brunner & Baccini, 1992; Obernosterer et al., 1998). Future CFC emissions from present stocks for example are estimated, even assuming a worldwide successful implementation of the Montreal protocol, to roughly equal the total added past emissions (Kleijn & Van der Voet, 1998). For heavy metals it was concluded in various studies that the emissions have been reduced to the expense of an increased speed of stockbuilding in society, and that a future increase of emissions may be expected as a result (Bergbäck, 1997; Guinée et al., in press).

When using MFA or SFA models for forecasting, stocks therefore should be a vital part. Flows and stocks interact with each other: stocks grow when the inflows exceed the outflows of a (sub)system and certain outflows of a (sub)system are proportional to the stocks. In this article we discuss some possibilities to estimate future outflows on the basis of information on current stocks. We use PVC in Sweden as a case in point. This case was partly based on a study by TNO and CML for Norsk Hydro (Tukker et al., 1996).

## 2. Methods and data

### 2.1 Flows and stocks in SFA

There are different types of relations between stocks and flows. We distinguish:

- the outflow is proportional to the stock's magnitude: the stock as a size buffer
- the outflow is a delayed inflow: the stock as a time buffer

*the stock as a size buffer*

Certain flows are dependent directly on the magnitude of certain stocks. For example, leaching of nitrate from the topsoil to the groundwater is not directly dependent on the addition of nitrates through fertilizers or atmospheric deposition, but is proportional to the stock (i.e., the concentration) of nitrate in the soil. The relation between the inflow of nitrate into the soil and the outflow through leaching is indirect, via the resulting increase of the stock in the soil. In this case the time of introduction of a nitrate-ion is not related to the time it leaches to the groundwater. In other words: the chance of leaching is equal for every nitrate ion present in the soil.

Modeling this type of flow-stock relation is relatively straightforward: first the magnitude of the stock has to be determined, for example by measurements or by massbalance calculation on the basis of records of past inflows and outflows, and then the outflow can be calculated as a simple fraction of the stock leading to a geometric distribution. For example the SFA model Flux uses this option (Boelens & Olsthoorn, 1998). Most environmental stocks conform to this type, and some emissions from economic stocks as well.

*the stock as a time buffer*
However, this approach is not valid for all types of stocks. An example is the modeling of waste flows from stocks of goods in society, e.g. PVC in roof gutters. In this case the waste generation depends on the stock of PVC in a different manner. Contrary to the nitrate example mentioned above, it does make a difference at what point in time a certain product entered the stock. For PVC gutters there will be more or a less a *FIFO* (first-in-first-out) type of regime; each individual gutter has a certain life span and on average the older specimens will enter the waste stage earlier than the newer ones. Thus not only the magnitude of the stock but also the age distribution of products in the stock determines the outflow.
In such a case the relation between the present size of the stocks and the future emissions and waste flows is often not straightforward and cannot be modeled easily (Huele & Kleijn, 1997; Huppes et al., 1997). This is even more true when a composite stock is regarded: the societal stock of PVC as it is today consists of a large number of products with widely varying average life spans.

## 2.2 Modeling the stock's outflow as a delayed inflow modified by life span distribution

One general rule of mass balances is that the mass inputs of a process equal the mass outputs. This rule is derived from the 18$^{th}$ century Lavoisier's *law of conservation of mass*. Lavoisier's law results in *the* most basic starting point for Material Flow Analysis: IN = OUT. It also applies in the case of stock modeling. Although the inflows have to equal the outflows in the end (in the steady state situation) this might never occur in reality due to changes in regimes and flows over time. If IN > OUT the substance which is studied will accumulate and stocks will be formed within the system. If IN < OUT there will be a negative accumulation and the stocks in the system will be depleted.

For our modeling of the outflow from stocks we have chosen to adopt the approach of regarding the outflow of the system as a delayed and reversed (negative) inflow. This approach has been used before for example for modeling the development of buildings (Gabathuler & Wüest, 1984) and is now adapted for the modeling of waste and emissions generation from societal stocks of products. In this view, the stocks are then a result of the combination of inflows and outflows over the years. The life span of the products determines the delay. This life span, although generally known or estimated as an average, will be distributed in some way: some individual products will be discarded earlier than others. To get an accurate picture of stock formation and depletion the distribution of life span should be known as well. However, empirical data on the life span distribution is often not available and the collection of such data can be very time-consuming.

An alternative for using empirical data would be to assume a certain life span distribution. Here there are various possibilities. Most commonplace would be to use a normal distribution: the deviations from the average are equal to both sides. The normal distribution was mentioned as an example of a known impulse response in the book of Baccini & Bader (1996). However, the choice for a normal distribution is rather arbitrary. One could imagine that in some cases there are arguments for another type of distribution. Skewed distributions such as Weibull's, which is already used in lifetime modeling (Stöcker, 1995) might sometimes be more appropriate. In some cases even more complicated distributions may apply, for example a curve with two peaks depending on the environment of use (corrosive vs sheltered), or a small peak very soon (the first-year deaths) followed by a larger one later on.

In this article, the *output = delayed input* approach described above is used to describe the economy as a system, that responds to an input of products (the input signal) with an equal output after a certain delay (the output signal). The shape of the output signal is determined by the shape of the input signal and by the transformation of this signal or in other words the signal processing by the system. The outflow in a certain year can thus be calculated as a combination of the inflows of earlier years and the life span distribution (or disposal function) of the product. In mathematical terms this is equal to *convolution.* In terms of Systems Theory: we use a dynamic, linear, deterministic model. In our example of PVC in Sweden, we use the normal distribution to describe the disposal function. In terms of Systems Theory: we assume two known impulse responses: one derived from unity and the other from a discretisized normal distribution.

### 2.3 Estimating the stock's inflow

The input signal as described above is the inflow of newly made products into the societal stock in a certain year. However, such an inflow will not only take place in one particular year but it will continue during a certain period. For example PVC-pipes have been used since the sixties and are still being produced. The inflow will change over time and decrease or increase according to the developments in supply, demand and policy measures, resulting in an input-curve over a number of years. If we want to predict future waste flows by the model described above, this input curve is important information.

Lacking such an input curve, several approaches can be taken. One is to construct it by collecting time-series data on past inflows. For some of the more bulky products, for example automobiles, this may be a good possibility, since production and trade statistics just might provide such data. When statistical data is lacking for the specific good, information could again be gathered via a time consuming process of interviews and digging into other data sources.

Another approach would be to circumvent the problem by collecting more information on the stocks themselves. A survey could be done via measurements, interviews and historic archives to find out the age distribution of the products involved. By combining the data on age-distribution with data on average life-time and life-time distributions the future waste flows then can be calculated. This approach is very valuable because it will result in database of more or less empirical data. An important disadvantage of this approach is however that it is very time consuming and therefore expensive, and that the odds for arriving at a sufficient database are not very high.

A third approach, applicable when either time or data are lacking, would be to estimate the future outflows on the basis of an assumed time-series for the inflow. The shape of the inflow curve can be based on the type of market which in which the product belongs. For example if we would talk about vinyl-clothing we would know the market would be a fashion-type market in which exponential growth (and decline) of consumption can occur. On the other hand the market for PVC-pipes seems to be described better by a model of linear increase in consumption. The thus assumed time-series of consumption (inflow) should again be combined with data on average life-time and life-time distribution to estimate the future waste flows (outflow).

In this paper, we take the third approach and screen a number of possible input curves, not only to predict future waste flows (and stocks) of PVC but also to assess the sensitivity of such predictions for assumptions.

## 3. Application of the modeling approach: five different ways for predicting future PVC waste flows

PVC is widely dispersed in society and is accumulated in anthropospheric stocks in various products, which at some time in the future will have to be processed as waste. A number of reasons can be given for the environmental relevance of the PVC stocks:

- there is a scientific debate about the role of PVC in the formation of dioxins in municipal waste incinerators (e.g. Born, 1992; Kanters, 1996);
- PVC may disturb the recycling processes of other plastics;
- together with PVC, problematic additives such as phthalates, lead, organotins and tin sulfide are accumulated. These additives may cause emissions both during use and during waste treatment.

It is therefore important to prepare adequate waste treatment facilities. In order to do this, information is required regarding the moment in time and the quantity in which PVC stocks will be offered for waste treatment. In a number of countries policies for phasing out of PVC in certain applications are being discussed.

The case of PVC in Sweden is used as an example to test the approach described above. We calculate waste flows (the output signal) as a result of the consumption (the input signal) of the three main PVC products: pipes, flooring and cables within the Swedish society (the system). In order to keep the analysis within limits, it has been assumed that PVC application will be phased out. In this way, the main statement from the above “today’s stocks are tomorrow’s emissions and waste flows” can be visualized. The only empirical starting point was Swedish data on stocks of PVC in various applications in 1994. The estimated amount of PVC and additives in stocks in Sweden in 1994 is given below in Table 1.

**Table 1: Estimated stocks of PVC and additives in Sweden in 1995 in ktonnes (Tukker et al., 1996)**

| | PVC (exc. additives) | phthalates | lead | organotin | SnS |
|---|---|---|---|---|---|
| **BUILDING** | | | | | |
| pipes | 919.4 | 0.0 | 6.9 | 0.0 | 0.0 |
| flooring | 397.7 | 152.3 | 0.0 | 0.1 | 1.8 |
| cables | 255.0 | 127.5 | 7.1 | 0.0 | 0.0 |
| window frames | 49.9 | 0.0 | 0.2 | 0.0 | 0.0 |
| pipes for elect. wire | 59.9 | 0.0 | 0.3 | 0.0 | 0.0 |
| coated building plate | 1.6 | 0.4 | 0.0 | 0.0 | 0.0 |
| roof covering | 30.0 | 7.5 | 0.0 | 0.0 | 0.0 |
| plastisol building plate | 45.0 | 18.0 | 0.0 | 0.5 | 0.0 |
| other build. app. | 57.4 | 0.0 | 0.3 | 0.0 | 0.0 |
| wall paper | 3.0 | 2.0 | 0.0 | 0.0 | 0.0 |
| ***SUBTOTAL*** | ***1819.0*** | ***307.6*** | ***14.9*** | ***0.6*** | ***1.8*** |
| **OTHERS** | | | | | |
| automotive | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| electrical equipment | 65.6 | 34.0 | 0.0 | 0.0 | 0.0 |
| manufacturing | 22.3 | 3.0 | 0.2 | 0.0 | 0.0 |
| office equipment | 23.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| other flex. film & foil | 15.0 | 3.8 | 0.0 | 0.0 | 0.0 |
| packaging | 28.2 | 7.1 | 0.0 | 0.0 | 0.0 |
| Grocery packaging | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| medical packaging | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| other rigid film & foil | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| other plastisol | 45.8 | 0.0 | 0.0 | 0.9 | 0.0 |
| medical tubes/hoses | 10.0 | 4.0 | 0.0 | 0.1 | 0.0 |
| other soft tubes/hoses | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| camouflage fabrics | 12.0 | 6.0 | 0.3 | 0.0 | 0.0 |
| other artif. leather | 15.0 | 9.8 | 0.0 | 0.0 | 0.0 |
| ***SUBTOTAL*** | ***236.9*** | ***67.5*** | ***0.7*** | ***1.0*** | ***0.0*** |
| | | | | | |
| **TOTAL** | **2055.9** | **375.1** | **15.6** | **1.7** | **1.8** |

To this data assumptions are added regarding the input curve, the life span and its distribution in order to arrive at the outflow.
Regarding the input curve three options are considered:

- The simplest assumption would be a constant inflow since the introduction of the different products. A constant inflow is an approximation of a stock that has reached a certain stable size, the inflow compensates the unavoidable losses.
- Another possible inflow curve would be the result of a linearly increasing inflow. This could represent a stock that is growing slowly and steadily, for example in line with population growth or welfare growth.
- A third possibility would be an exponential increase since the introduction of the products. An exponential growth may be imagined for new products conquering markets rapidly, such as fashions and rages, or a new material replacing an old one.

Two options are considered in relation to the life span distribution:

- The simplest option which may serve as a reference is to assume an exactly known life span, which is not distributed
- As a second option, a discretisized normal distribution is considered.

Out of a combination of these options, five models are generated. These are presented below in Table 2.

**Table 2: Chosen models**

| | Inflow | lifetime distribution |
|---|---|---|
| **Model 1** | constant $I_t = a$ | average lifetime used as exact lifetime |
| **Model 2** | linear increasing $I_t = at$ | average lifetime used as exact lifetime |
| **Model 3** | exponential increasing $I_t = e^{at} - 1$ | average lifetime used as exact lifetime |
| **Model 4** | constant $I_t = a$ | discretisized normal distribution |
| **Model 5** | linear increasing $I_t = at$ | discretisized normal distribution |
| **Model 6** | exponential increasing $I_t = e^{at} - 1$ | discretisized normal distribution |

In all models the following starting points have been used:

- The stocks' sizes including additives have been used, i.e. 926.3 ktonnes for PVC pipes, 551.9 ktonnes in PVC flooring, and 389.6 ktonnes for PVC cables.
- The starting year for application of PVC was 1960 for pipes, 1975 for flooring, and 1965 for cables. These assumptions are educated guesses.
- The average life span is 60 years for pipes, 15 years for flooring, and 30 years for cables, also educated guesses.
- The standard deviation of the average life span, used in models 4, 5 and 6, is assumed to be roughly one sixth of the life span, i.e.10 years for pipes, 3 years for flooring, and 5 years for cables.
- The application of PVC in pipes, flooring and cables will linearly decline from 1995 to zero 2010 due to an assumed phasing out policy. This assumption is not related to any policy but was made to illustrate the time buffering of stocks.

In the next section, the results of the calculations are presented.

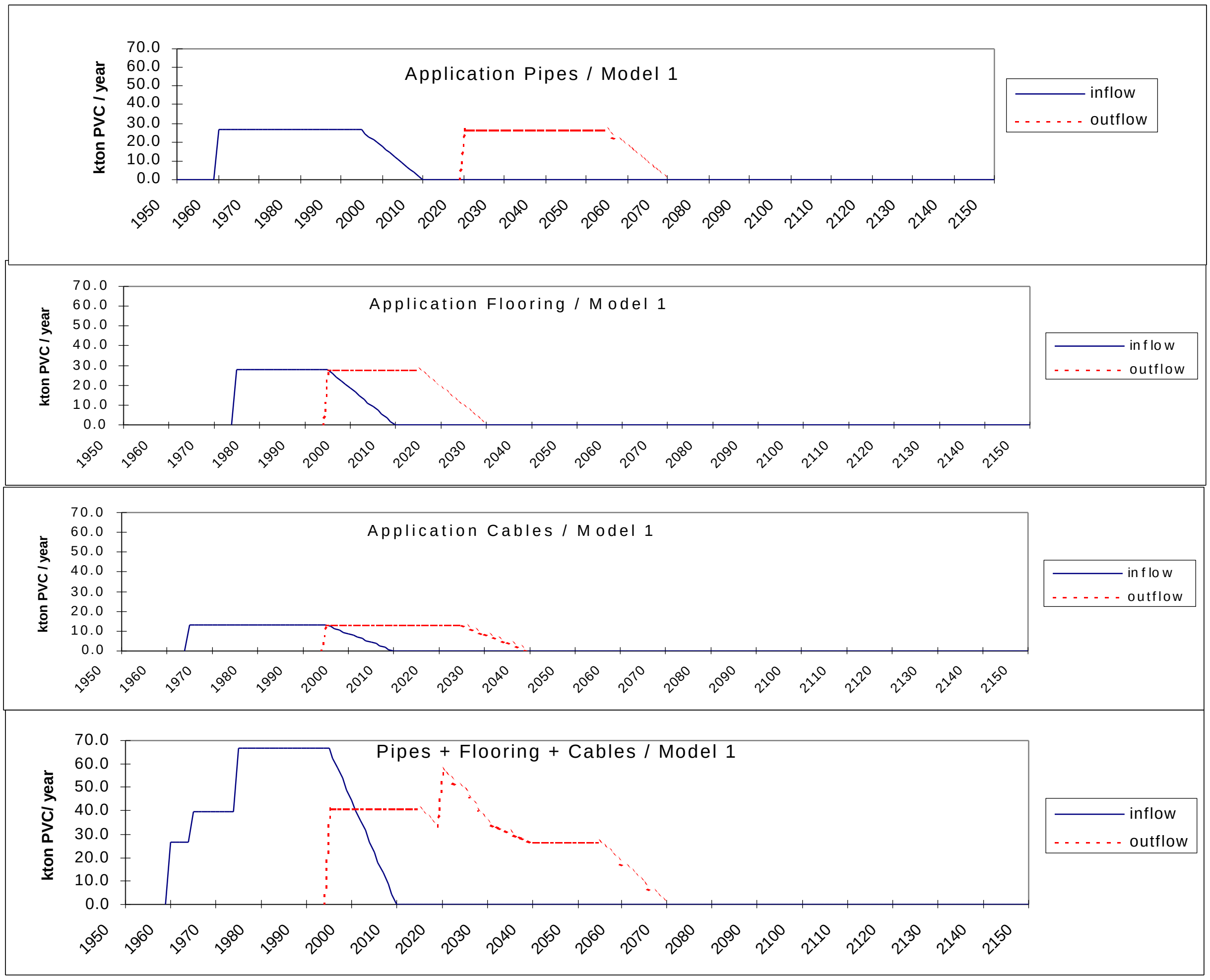


**Figure 1: Input and Output curves for all appliactions of PVC using model 1.**

## 4. Results

Figure 1 contains the input and output curves for all applications using model 1. In Figure 2 input and output curves are shown for the application of PVC in pipes using all six models. We can see the output curve as a delayed input curve, the delay of course depending on the assumed life span for each application. The influence of the assumption regarding the shape of the input curve also shows quite clearly. In Model 3, the exponentially increasing inflow, the peak in waste generation is highest, and leads to predictions about generated waste at least a factor 2 higher than the other two models. The influence of the assumed normal distribution of the life span is also visible. The outflow curves are smoother, are more extended in time, and have lower and even earlier peaks than the outflow curves of the models with a fixed life span.

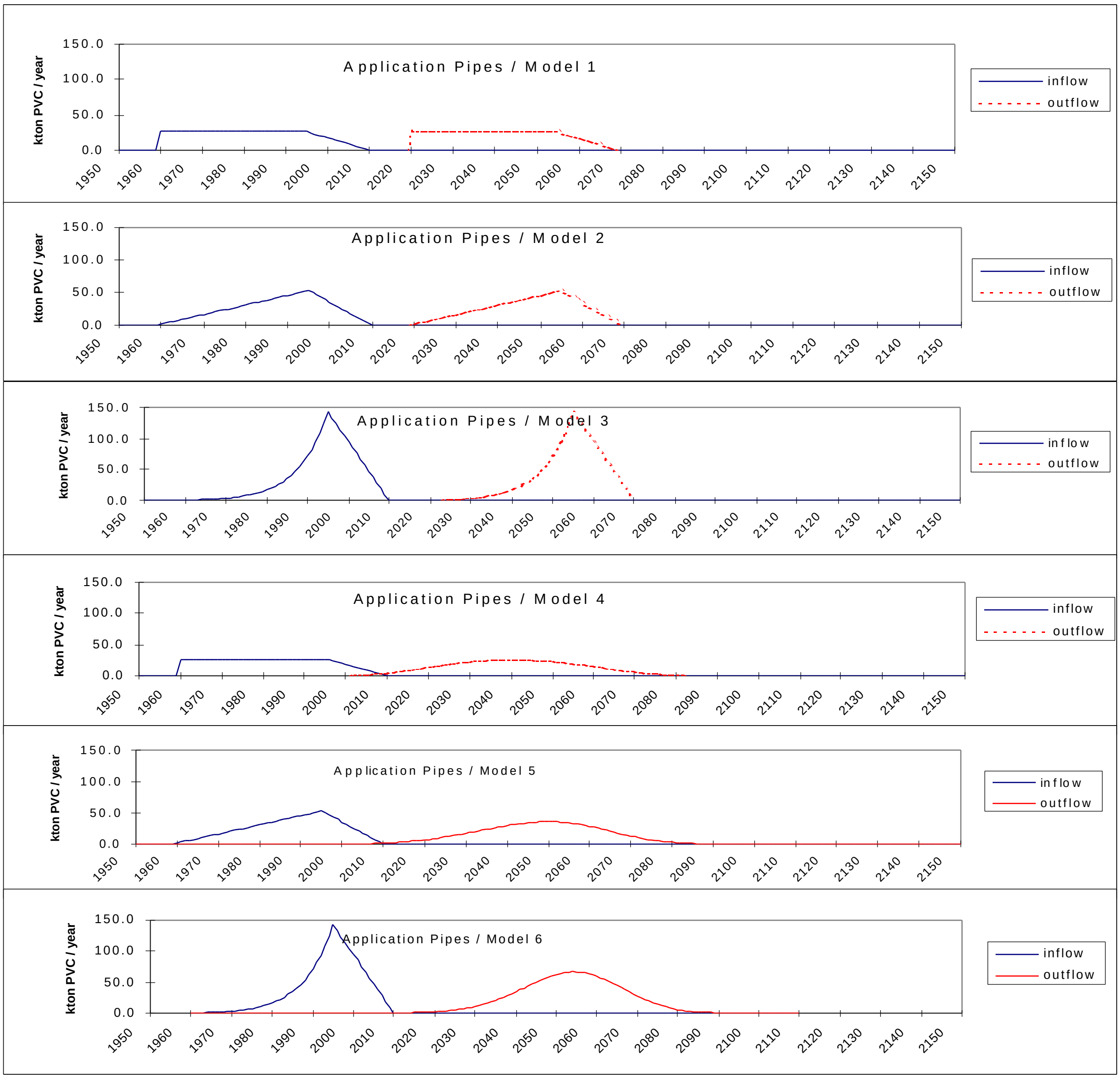


**Figure 2: Input and Output curves for the PVC in the application pipes using all 6 models.**

In Figure 3 we see the development of the societal stocks of PVC in pipes through time using all six models. The magnitude of the stock is, as might be expected, much larger than the inflow or outflow. The influence of the type of input curve which is used is important .The biggest stock is reached when an exponential increasing inflow is assumed (model 5 and 6). The influence of the life span distribution is hardly visible in the stocks' sizes.

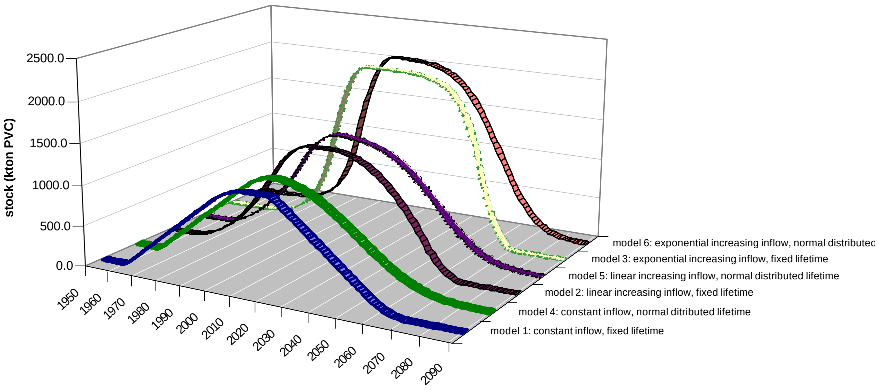


**Figure 3: Development of societal stocks of PVC in pipes through time using all six models.**

Figure 4 contains the results of the combination of the three major PVC applications on the total outflow of PVC over time. Even with the first model, with the simple assumptions of a constant inflow and an exactly known life span, the combination leads to a rather complex curve. Most models generate two peaks. The first peak occurs between 2010 and 2020 and is due to flooring and cables becoming waste. The second peak between 2050 and 2060 comes from discarded pipes. Again we can see the influence of the assumptions regarding the input curve: the exponential increase leads to very much higher peaks than the other two inflow curves. The normal distribution smoothens the curves again, for the constant inflow assumption even to the point of smoothing over the second peak. The first peak is somewhat lower and again somewhat earlier in time. The moment in time where the outflow curve ends is delayed from 2070 until roughly 2100.

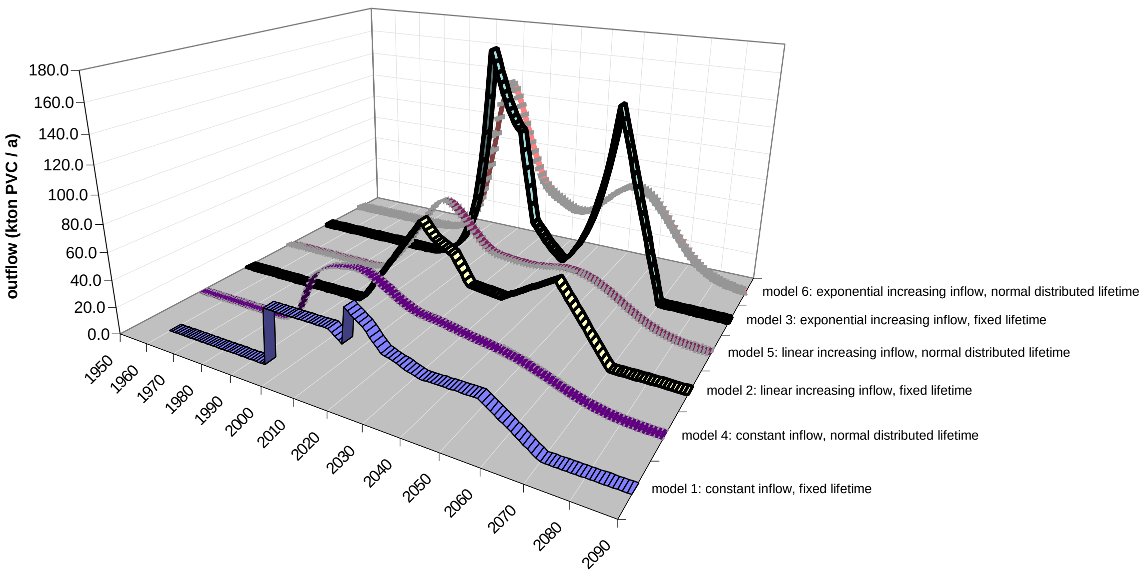

**Figure 4: Ouflows of PVC as a result of the combination of three major PVC-applications using all 6 models.**

Figure 5 finally contains the development of the total stock of PVC over time as a result of the three major PVC applications. Again, the exponentially growing inflows are is the odd one out, the other five models lead to rather similar results. Especially intersting is the fact that adding a normal distributed lifespan only results in minor changes in the stocks. The influence on the outflows (figure 4) is much larger.

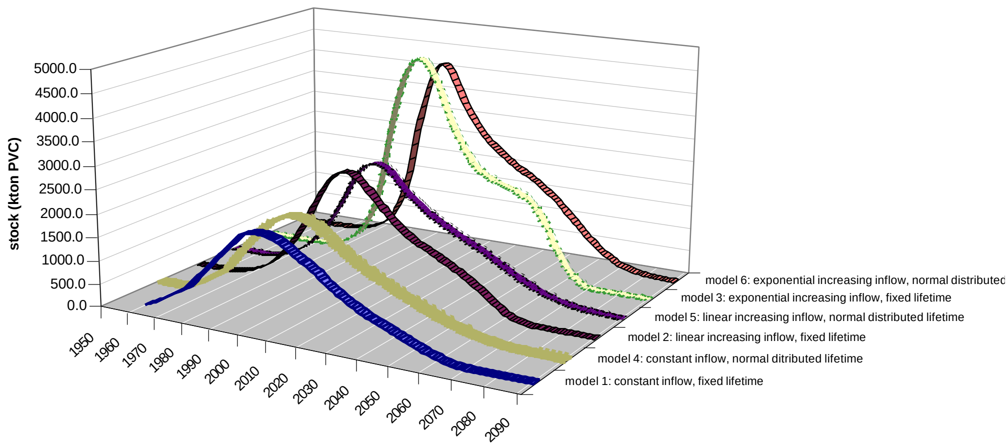


**Figure 5: Development of Societal stocks of PVC as a result of the three major PVC applications.**

## 5. Discussion and Conclusions

This paper contains a description of a possible approach to identify and estimate future waste flows from societal stocks. Although this approach is very preliminary and the PVC case rather sketchy, some conclusions can be drawn already.
If we look at the results in terms of a potential waste processing problem, we can see that a peak in the generation of PVC waste will rebound long after the application has been phased out. PVC will continue to be part of the generated waste until a century afterwards. Although these results are not directly applicable - the stock estimates are very rough and there is no phasing out policy for these applications - this type of information may be valuable for waste management policies.

If we regard the influence of the different variables on the results, we can see that the shape of the input curve is the most important. It might be advisable therefore to derive such input curves from real data whenever possible. In some cases - as in the case of cars - such data are available in statistics. However if stocks of less bulky products are involved, it may not be easy to arrive at an input curve from statistical data. In such cases assumptions are required. Other information, such as product and substance characteristics, then must be used to make such assumptions. This could be a line of investigation worth exploring for more than one reason: not only is a good estimate required when data are lacking, but it could also very much streamline the procedure because a very limited amount of data may go a long way. This could greatly enhance the applicability for environmental policy.

The impulse response appears to be less influential. Adding a discretized normal distribution for the lifespan somewhat lowers the peaks and delays the time of fade-out of the signal, but is does not alter the shape of the output curve dramatically. It could be concluded therefore that for a first rough approximation an exactly known life span may be sufficient. If more precise information is required the distribution becomes more important: in the case of PVC the normally distributed life spans did not only lead to lower peaks, but in some cases to an earlier occurrence of the peaks. Possibly other distributions - especially very skewed ones - have a larger impact. This must be investigated further.

Stock modeling therefore appears to be useful. The approach of combining the inflow curve with a delay and a life span distribution to arrive at an estimate for the outflow curve certainly works, although very little can be concluded about how realistic the results may be. The approach must be tested with empirical data to obtain more insight.

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Figure 1: Development of the inflow of new products and the outflow of waste of the three major PVC applications using model 1
1a: PVC pipes, inflow and outflow
1b: PVC flooring, inflow and outflow
1c: PVC cables, inflow and outflow
1d: pipes, flooring and cables combined, inflow and outflow

Figure2: Inflow and outflow of pipes using the six different models

Figure 3: Development of the stocks of PVC pipes assuming different models

Figure 4: Development of the generation of PVC waste as a result of the dynamics of the three major PVC applications, assuming different models

Figure 5: Development of the PVC stock as a result of the dynamics of the three major PVC applications, assuming different models