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A DYNAMIC SIMULATION MODEL FOR MATERIALS-PRODUCT-CHAINS: AN APPLICATION TO GUTTERS*

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ABSTRACT

A descriptive dynamic model is presented to study the impacts of various policies aimed at reducing the use of materials in materials-product-chains (M-P chains). An M-P chain describes the flows of materials and products on a physical and a monetary level to allow assessments of strategies affecting both material and economic characteristics. Recycling and substitution are included in the model, which is applied to gutters and associated materials flows of zinc and polyvinyl chloride. Economic and material impacts of several scenarios are assessed.

1. INTRODUCTION

Many studies have characterized the flow of materials from the extraction from the environment to the disposal of waste into the environment. These studies often lack an explicit treatment of products and economic and technical processes. Here products, materials, and the link between them are studied. Policies are investigated that patterns of materials use. In materials-product-chains (M-P chains) a specific subset of the flows of materials and products is described. A simple dynamic simulation model is presented to study the impacts on M-P chains of various economic and policy developments aimed at reducing the use of materials. In this simulation model different decision-making processes

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and their interactions are described to provide insight into several economic mechanisms which influence the environment. The model aims at tracing the effects of such changes as accumulation, substitution, and recycling. Various scenarios are studied to assess the influence of the distribution of the demand over the products and certain developments on the M-P chain over a period of time. The scenarios studied in the dynamic simulation model are a base scenario and four policy scenarios.

In Section 2 the concepts of materials balances and product flows and their links are presented. In Section 3 the M-P chain for gutters is explained. In Section 4 the "time pattern" for gutters is formally described. The dynamic simulation model is presented in Section 5. In Section 6 the scenarios, the control variables and the indicators of the model are given. Section 7 discusses the results of the scenarios of the simulation model. A final section offers conclusions and indications for further research.

2. CONCEPTS

An important concept in studying materials-product relationships is that of materials-balance (MB). This concept imposes an accounting identity at the materials level: flows into a system equal flows out of the system, plus/minus net accumulation within the system. The concept can be applied to individual systems of production and consumption, or to entire economic or environmental systems. There have been many studies describing materials flows through the economy using models that formalize the MB-concept since it was introduced by Ayres and Kneese [1].

Inputs of materials in a process or system must end up as either accumulation of stocks or materials outflows. In most MB-studies the flows of one or more specific "materials" are modeled. The term "materials" is used to refer to single elements (e.g., cadmium in [2]) or compounds (e.g., steel) or even materials (e.g., plastics in [3]). At the level of single elements, the law of conservation of mass provides a rigorous check on the calculation of materials flows. This check is less rigorous as more complex compounds or materials are the object of the analysis.

A product life cycle on the other hand, represents the flows of products through the economic process, from primary production through consumption. By extending the product life-cycles with materials and environmental effects of product flows one can use the concept in environmental economic studies (see [4, 5]).

In M-P chains [5] material flows and product life cycles are integrated in order to give a broader view of the flows of materials and products and shed light on the underlying processes operating in both economy and environment. This means that the transformation of materials into products and of products into materials are both considered. For these conversions MB-conditions can be used to quantify the materials transformed. M-P chains can be regarded as subsets of linked materials and products flows that can deliver one or more end service(s). With M-P chains one may investigate complements, substitutes, and recycling on both the product and materials level. Various theoretical models for optimizing costs, given costs of recycling of materials and products and of waste treatment, of M-P chains are given in Kandelaars et al. [6].

3. GUTTERS AS A CASE STUDY

This article focuses on one particular class of products, gutters, providing one particular service, removing rain water from the roofs of houses. In this M-P chain two types of gutters will be compared, zinc and polyvinyl chloride (PVC) gutters. The case of gutters is of interest because zinc gutters consume a considerable part of the total amount of zinc (a non-renewable resource) used in the Netherlands. Until recently zinc was not considered to cause environmental problems; this perhaps is related to the fact that it is a necessary trace-element for human beings, animals, and plants. However, two main problems have emerged as a result of the increased use of zinc: 1) high concentrations of zinc may harm crops in agricultural soil and organisms in surface water; and 2) the stock of zinc ore in the environment is exhaustible [7]. The main environmental problems caused by zinc are aquatic toxicity, acidification, landscape deterioration, and the extraction of the toxic material cadmium, which is a trace element in zinc ore [8, 9].

The most important environmental impacts of the alternative PVC gutters are the use of energy and the releases of several toxic substances, such as chlorine. The transport of chlorine by rail poses a significant environmental risk [10]. In this article it is assumed that diminishing the use of zinc has a higher priority than reducing the use of PVC. Therefore, the central focus of this article is to diminish the use of zinc. Although both PVC and zinc gutters have negative impacts on the environment, the choice between zinc and PVC gutters is mainly determined on the basis of their prices and the preferences of the consumers, especially construction firms.

In the Netherlands the market for gutters is dominated by zinc gutters because they are strong, attractive, cheap, and traditionally used. In several other countries of the European Union this leading position is not found; for instance in France PVC gutters dominate the market [11].

Gutter services will be measured in functional units. As a functional unit the length of a gutter for an average house is chosen, which is 12 meters [11]. The weight of this functional unit depends on the type of gutter: a zinc gutter of 12 meters weighs 29.6 kilograms and a PVC gutter of the same size 16.1 kilograms [11].

A gutter service requires three elements: a gutter, a fastening-piece, and a waste-pipe. Besides the gutters, the fastening-pieces are of substantial interest, because the amount of materials needed for a fastening piece depends on the type of gutter. The fastening-pieces for both types of gutters are made of the same material, galvanized steel, but in different quantities. The waste-pipe is not included in the model because such pipes are the same for both types of gutters and therefore irrelevant for a comparison.

Zinc gutters are not reused, but a part of the zinc content of a gutter is recycled. Zinc gutters are 99.8 percent zinc, a concentration that makes recycling through melting economically and environmentally attractive. In the Netherlands used zinc gutters are collected and transported to Germany for recycling. The zinc, which is imported to the Netherlands, is partly made from zinc ore and partly from remelted zinc. No data are available on the fraction made from remelted zinc, i.e., recycled or secondary zinc [7].

Differences between PVC and zinc gutters are that 1) PVC gutters have a shorter life span than zinc gutters and 2) the quality of PVC gutters is inferior to that of zinc gutters. After use, PVC can be recycled provided that it is not contaminated by other materials. The presence of other materials changes the materials characteristics and greatly complicates the recycling possibilities. In the case of PVC gutters, the PVC is contaminated by glue, which restricts many high-grade recycling options. Unlike zinc recycling, PVC recycling is economically unprofitable at the current prices: the costs of producing new PVC are lower than of recycling PVC.

Finally, the fastening-pieces of both zinc and PVC gutters are made of galvanized steel which is as yet not recycled because of technical and economic constraints. Research underway at Hoogovens, the Netherlands, and elsewhere, make it technically possible and economically rewarding to recycle zinc out of galvanized steel [11]. The quantities of zinc, PVC, and galvanized steel that are not recycled enter the environment as waste flows.

Data on the production, use, and disposal of gutters for the base year can be found in Fraanje [7, 8, 11, 12]. The base year is taken to be 1990 because it is the most recent year for which a complete set of data is available. The time horizon of the model simulation is set at sixty years, in order to allow for the comparison of the two types of gutters with different lifetimes: thirty years for zinc gutters and twenty years for PVC gutters.

4. FORMAL DESCRIPTION OF THE TIME PATTERN OF GUTTERS

In this section a formal description is given of the demand for gutters and the stock of gutters in use over a period of time. The demand for gutters depends on the number of replaced gutters and the number of newly built houses for which gutters are needed. The yearly demand for gutters, D_t, consists of replaced gutters, R_t, and gutters needed for newly built houses, N_t.

$$D_t = R_t + N_t \qquad (1)$$

The number of gutters that is used up at time t is equal to the demand at (t-T), D_{t-T} with T equal to the life span of gutters. D_{t-T} by definition originates from existing houses. These can be renovated which involves a replacement of the gutters. This replacement demand is R_t. Alternatively, these houses are demolished rather than renovated, which gives a flow of disposed gutters, W_t. Thus,

$$R_t + W_t = D_{t-T} \tag{2}$$

The replacement demand, R_t, is a fraction s_t of the amount of gutters that are used up:

$$R_t = s_t D_{t-T} \tag{3}$$

The total stock of gutters at time t, G_t, is equal to the stock of gutters at time (t-1), G_{t-1}, plus the new gutters at time t, N_t, minus the disposed gutters at time t, W_t.

$$G_t = G_{t-1} + N_t - W_T \tag{4}$$

From equations (1) and (2) it follows that $N_t - W_t = D_t - D_{t-T}$. With (4) this results in:

$$G_t = G_{t-1} + D_t - D_{t-T} \tag{5}$$

With $D_t = 0$ for $t \leq 0$, repeated substitution of (4) in (3) leads to:

$$G_t = \sum_{r=t-T+1}^{t} D_r \tag{6}$$

The total stock of gutters, G_t, is equal to the demand for gutters of the last T years, since T is the life span of gutters.

In Figure 1 time patterns for the most relevant variables are shown and related to one another. These variables are 1) the gutters needed for newly built houses at time t, N_t, 2) the replaced gutters at time t, R_t, 3) the total demand at time t, D_t, and 4) the stock at time t, G_t. In the simulation model the demand for gutters in 1960 will be replaced in the base-year 1990, with the sixty-year time horizon the demand for and the stock of gutters is tracked for the period 1960-2050. This period and these variables will be used again in the next sections where the model that is used to explore several policy scenarios is described.

5. MODEL DESCRIPTION

The dynamic simulation model is based on a given demand for gutters, which is met by two types, zinc and PVC. The model has eight submodels: three at the product level, three at the materials level, one for the extraction of ores and one for the calculation of prices and costs. In Figure 2 these eight submodels and their links are displayed.

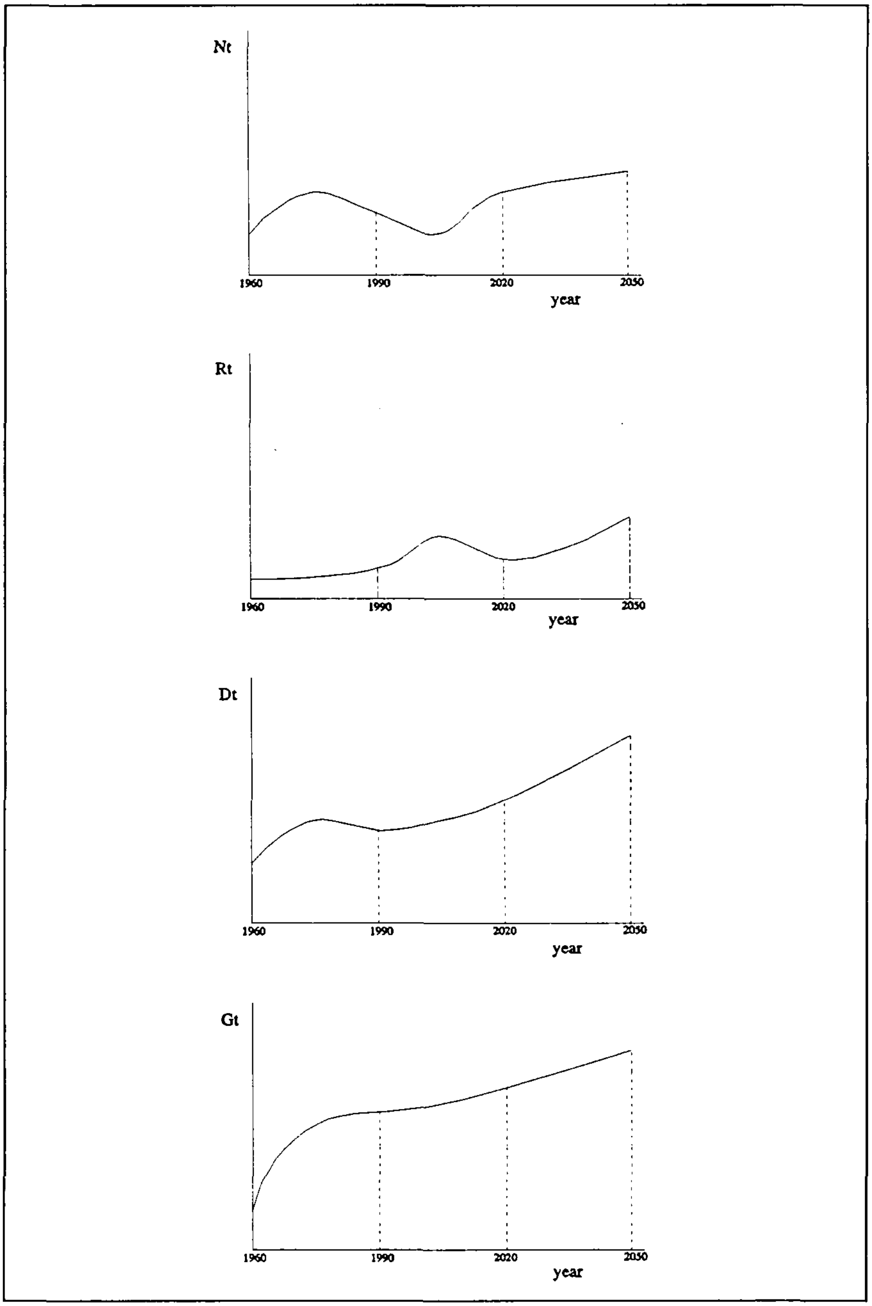

Figure 1. The demand for and the stock of gutters at time t.

In this section a description is given of the submodels. The appendix contains the initial conditions and equations.

Gutter Submodel

Here the demand, the accumulation in the economy, and the waste of gutters are modeled. In the product submodels gutters are measured in functional units. In the model the yearly total demand for gutter service which has to be met is exogenously given. In the base-year 1990 the number (stock) of gutters in the economy is 2,660,560. Every year one portion of these gutters is replaced and another is demolished because of the demolition of the house to which it belonged. The replaced gutters and the gutters needed for newly built houses form the yearly demand for gutters. Note that gutters are not yet recycled at a product level.

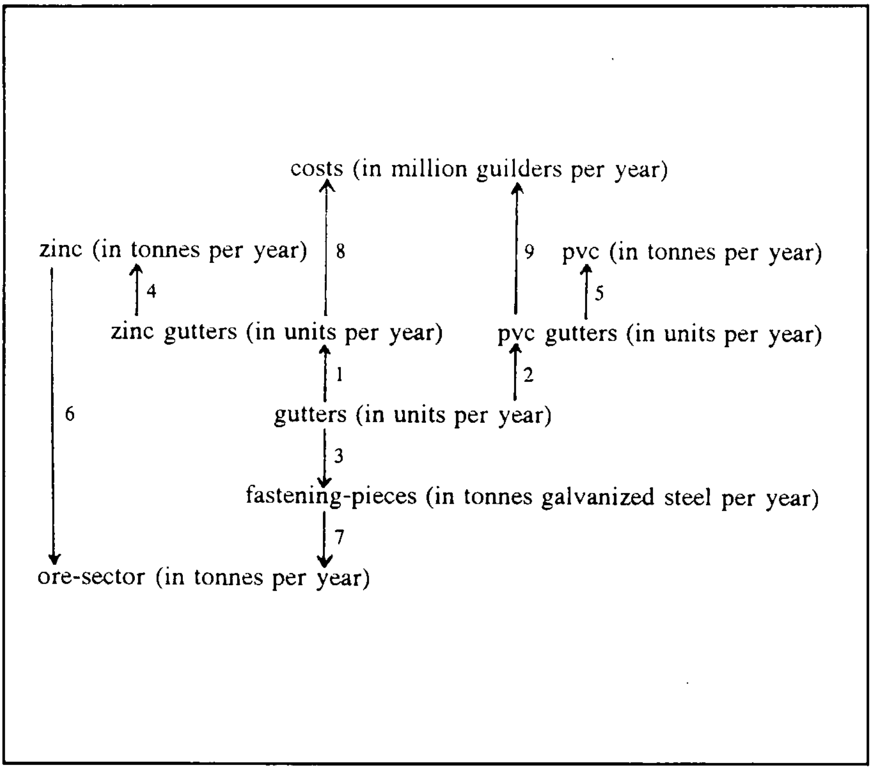

Figure 2. Basic simulation model for linking gutters demand to materials flows.

Zinc and PVC Gutter Submodels

These two submodels describe the production of zinc and PVC gutters. The demand for gutters is allocated to zinc and PVC gutters (arrows 1 and 2). This division of the demand for gutters into the two types of gutters is one of the major decision variables of the model. This decision variable also determines the quantities of zinc and PVC needed to satisfy the demand for gutters. The sum of the gutters in the zinc and PVC gutter submodels equals the number of gutters in the gutter submodel.

Fastening-Pieces Submodel

As stated above, a complete gutter consists, besides the gutter itself, of galvanized steel fastening-pieces. The fastening-pieces are measured in tonnes of galvanized steel to have an equal measure for both types of gutters. The number and type of fastening-pieces which are made, demolished, and renovated depend directly on the allocation of the demand for gutters (arrow 3). Galvanized steel is not recycled.

Zinc, PVC, and Galvanized Steel Submodels

Here the quantities of zinc, PVC, and galvanized steel are measured in tonnes. The zinc (PVC) submodel is directly linked with the zinc (PVC) gutter submodel, indicated by arrows 4 and 5. The gutters, which are measured in functional units in the product submodels, are connected with the materials submodel by converting the number of products into the amount of materials. The conversion from functional units to tonnes is made using a known conversion factor. The materials needed for both gutters are calculated at the product level. In Figure 3 the materials flow submodel of zinc shows the flows of zinc from the environment through the economy and back to the environment.

Ore Sector Submodel

A submodel for metal ores is added to describe and analyze the rate of extraction needed to meet the demand for gutters. Extraction may result in the depletion of zinc ore. Ores are needed for the production of zinc and galvanized steel (arrows 6 and 7), which makes the extraction rates depend on the demand for zinc and galvanized steel. Ores are measured in tonnes.

Prices and Costs Submodel

In this economic submodel the costs of meeting the demand for the MP chain and the revenues of re-using materials are calculated. The costs are directly linked to the use of zinc and PVC gutters (arrows 8 and 9). The costs involved are the prices of the two types of gutters and the revenues of used materials. These

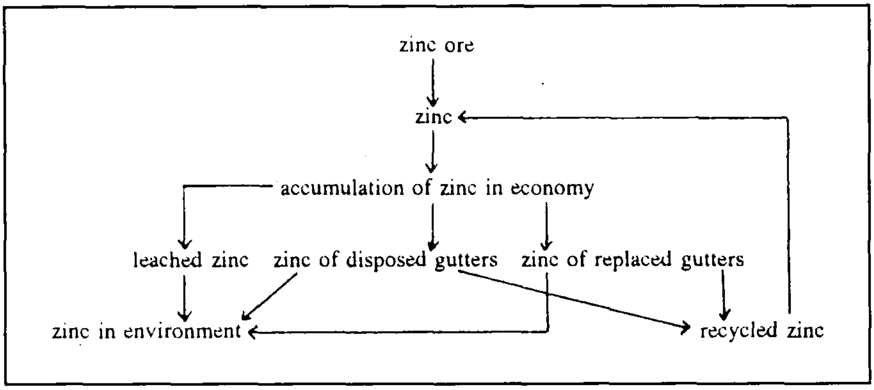

Figure 3. A materials flow model of zinc in environment and economy.

revenues of used zinc, PVC, and galvanized steel together with the prices of zinc and PVC gutters, determine the allocation of the demand over the two types of gutters and the materials used. The net costs equal the costs of buying gutters minus the revenues of used materials. The price of one kilogram of new zinc equals the price of recycled zinc, which makes it reasonable to assume that the difference between the price of recycled zinc and the revenue of used zinc equals the costs of recycling.

6. SCENARIOS, CONTROL VARIABLES, AND INDICATORS

Five scenarios are analyzed by way of dynamic simulation. These scenarios focus on the influences of preferential, policy, and economic change, on materials flows through changes in M-P chains.

The following scenarios are studied:

1. Base scenario;
2. Preferences shift scenario;
3. Product charge scenario;
4. Recycling scenario; and
5. Mixed scenario.

The base scenario, in which the exogenously determined variables are held constant, serves as a reference scenario for the other scenarios. The control variables are 1) the allocation variable, which distributes the demand for gutters over the two types of gutters, 2) the price of a zinc gutter, which influences the costs of meeting the demand and the distribution of the demand, 3) the price of recycled zinc, which influences the costs and the percentage and quantity of zinc that is recycled, and 4) the price of recycled PVC, which influences the cost and the percentage and quantity of PVC that is recycled.

In Table 1 the scenarios and the associated levels of the control variables are summarized. In the column of the base scenario the values of the control variables are given; in the columns for the other four scenarios the values of the control variables are only given when they differ from the base scenario.

For a comparison of the various scenarios the following clusters of performance indicators are distinguished: 1) the quantities extracted from and disposed into the environment, 2) the levels of recycling, 3) the allocation of the demand for gutters, and 4) the prices and the net costs of satisfying the gutter demand.

Base Scenario

In the base scenario all exogenous variables remain stable over time at the level of the base-year 1990: demand for gutters, allocation over zinc- and PVC gutters, recycling percentages for PVC, zinc and galvanized steel, demolition, and replacement of gutters. The data for the base scenario are obtained from various sources which are mentioned in the model description of Sections 3 and 4.

Preferences Shift Scenario

In the preferences shift scenario the allocation variable is set at a different level and is assumed to change over time to analyze the impact of a change in the

Table 1. The Scenarios with Their Control Variables

Scenario	Base	Preferences Shift	Product Charge	Recycling	Mixed
Control variable					
Allocation variable	0.8	max (0.8–0.03t,0.2)			
Price of zinc gutter	180		min (180+5t,300)		min (180+5t, 300)
Price of recycled zinc	1			2	2
Price of recycled PVC	0			1	1

distribution of the demand on economic and environmental variables. Therefore the distribution of the demand for gutters into zinc- and PVC gutters changes over time. In this scenario the total demand of gutters is met increasingly by PVC gutters, which could be the result of information or education by the government on the environmental implications of the two types of gutters. In this scenario the percentage of the demand for gutters changes from 80 to 20 percent in twenty years, all the other variables stay the same, e.g., the price for a zinc or PVC gutter remains 180 guilders. The shift in the allocation of the demand alters the quantities of zinc and PVC needed and in turn the extraction from and disposals to the environment. The percentages of recycling do not change, but the quantities do, as a result of the changed use of materials.

Product Charge Scenario

This scenario differs from the base and preferences shift scenario because now the allocation of the demand depends on the prices of the two types of gutters. In this scenario the price of zinc is raised because of a charge which increases over time. This charge influences the distribution of the demand over the two types of gutters. In reality the world price of zinc has been decreasing. However, in this scenario the government is assumed to raise the price of zinc gutters annually up to 300 guilders per kilogram, in order to decrease the use of zinc in the economy.

Recycling Scenario

Prices of used materials can change due to changes in market conditions (e.g., costs of disposal of materials) or to government inventions (e.g., subsidies for recycling and deposit-refund systems). In this scenario the government gives a subsidy to used zinc and used PVC. As a result it may become more attractive to collect and recycle the zinc from gutters. The percentage of zinc recycling is assumed to rise linearly with a price increase of used zinc, i.e., (80+ price used zinc*10) percent. Note that the price of used zinc is expressed in guilders per kilograms. The percentage of recycling of PVC gutters also rises because of an increase in the price of used PVC induced by a government subsidy. In 1990 used PVC does not have a positive price because it is cheaper to make new PVC than to recycle used PVC. When the price of used PVC rises, construction companies will have an incentive to collect PVC gutters separately for recycling. The percentage of PVC recycling is assumed to be (70+ price of used PVC*10) percent. In the model the recycled PVC is assumed to be used for gutters again. In practice the recycled PVC from gutters does not have the same quality as new PVC and therefore cannot be used for PVC gutters again.

Mixed Scenario

The mixed scenario combines the two previous scenarios. Both prices of zinc gutters and used zinc and PVC increase, so impacting the allocation of the demand and the percentages of recycling for both materials.

In the next section the results of these scenarios will be presented.

7. OVERVIEW OF THE RESULTS

The simulation results of each of the five scenarios are summarized in Table 2. In the columns of the scenarios the differences with the base scenario are represented with + (–) for a positive (negative) change, ++ for a considerable change, 0 if there is no change and ≈0 if there is a very small change.

Results of the Base Scenario (Figures 4, 5, and 6)

In the base scenario the exogenously determined variables remain stable over time. During the first thirty (20) years after the base year the stock of zinc (PVC) gutters is either replaced or disposed of as waste gutters because of demolition of the house. The number of newly built houses is assumed to remain constant over time. The demand for gutters (gnewin in Figure 4) increases annually because the number of newly built houses is greater than that of demolished houses and gutters (see line 1 in Figure 4). The allocation of the demand for gutters, r in Figure 4, does not change, so that the demand for gutters remains at 80 percent of the total demand (see line 4 in Figure 4), with the demand for zinc and PVC gutters over time presented in Figure 4 by zgnewin and pgnewin (lines 2 and 3 in Figure 4 respectively).

Table 2. Overview of the Results of the Scenarios

Scenarios	Preferences Shift	Product Charge	Recycling	Mixed
Economic variables				
Demand gutters	+	+	0	+
Allocation variable	–	–	0	–
Net costs	+	+	–	+
Environmental variables				
Recycling % zinc	0	0	+	+
Recycling % PVC	0	0	+	+
Stock zinc ore	++	++	+	++
Zinc waste in environment	–	–	–	–
PVC waste in environment	+	+	+	+
Galvanized steel waste in environment	≈0	≈0	≈0	≈0

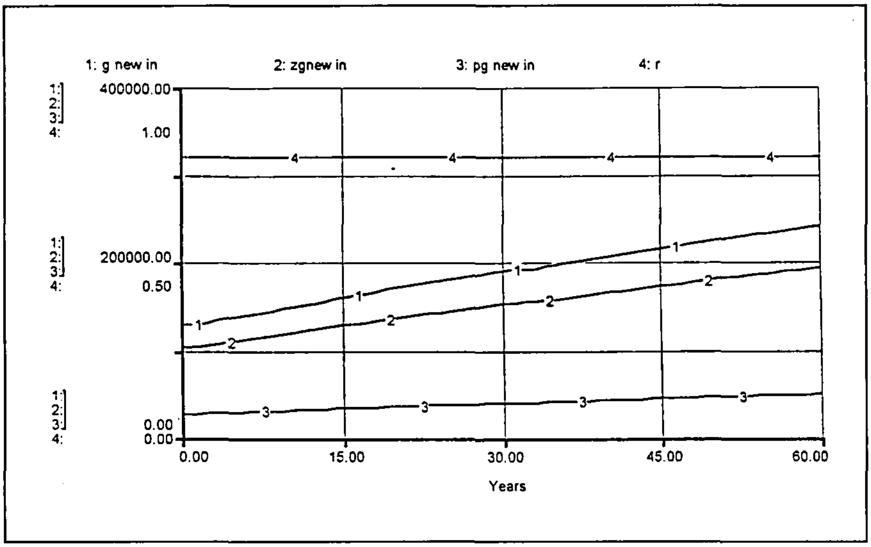

Figure 4. Allocation of the demand over zinc and PVC gutters, base scenario.

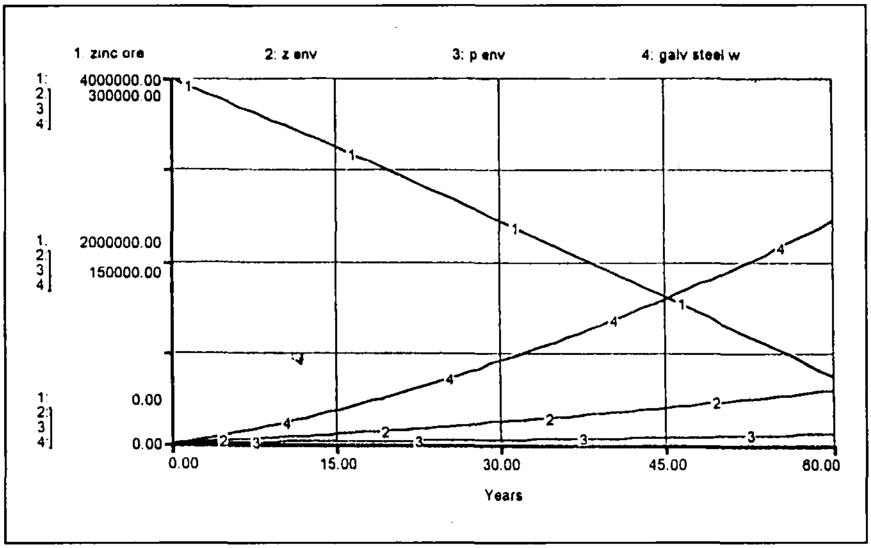

Figure 5. The extraction of and the disposal to the environment, base scenario.

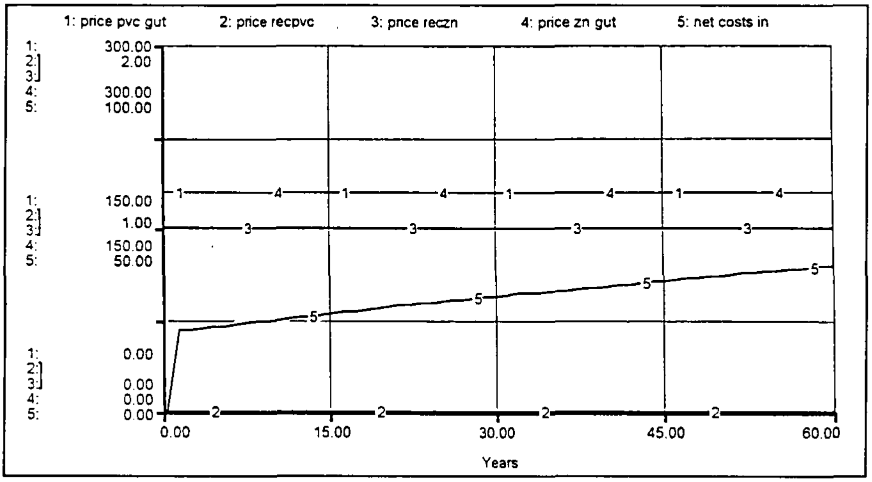

Figure 6. Prices and net costs of satisfying the demand, base scenario.

This demand has a substantial influence on the stock of zinc ore as can be seen in Figure 5 (line 1). The results of the disposal of zinc, PVC, and galvanized steel into the environment are represented in Figure 5 by z env, p env, galv steel w respectively. Especially the waste flow of galvanized steel into the environment is significant in relation to those of zinc and PVC.

The prices for the products and for the recycled materials remain stable over time (see lines 1-4 in Figure 6). The net costs of satisfying the demand, which are the costs of the demand for gutters minus the revenues of used materials, rise every year because of an increasing demand (see line 5 in Figure 6).

Results of the Preferences Shift Scenario (Figures 7 and 8)

Because of a growing environmental awareness preferences are assumed to shift in favor of PVC gutters. Hence, the share of the demand allocated to PVC gutters increases. As a consequence the number of renovated gutters rise in comparison with the base scenario because PVC gutters have a shorter lifetime.

As an effect of the use of more PVC gutters, the net costs over sixty years will rise because of two reasons: first, the shorter life span of PVC gutters asks for more gutters and therefore higher costs; and second, used PVC does not have a positive impact on total costs as does used zinc.

The total use and disposal of zinc decreases (z env in Figure 7) while the amount of disposed PVC rises (p env in Figure 7). The waste of galvanized steel

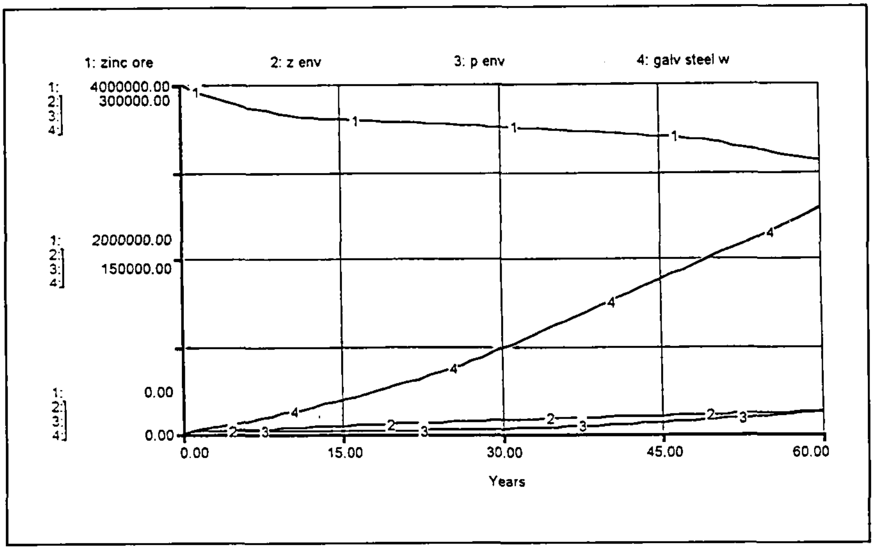

Figure 7. The extraction of and the disposal to the environment, preferences shift scenario.

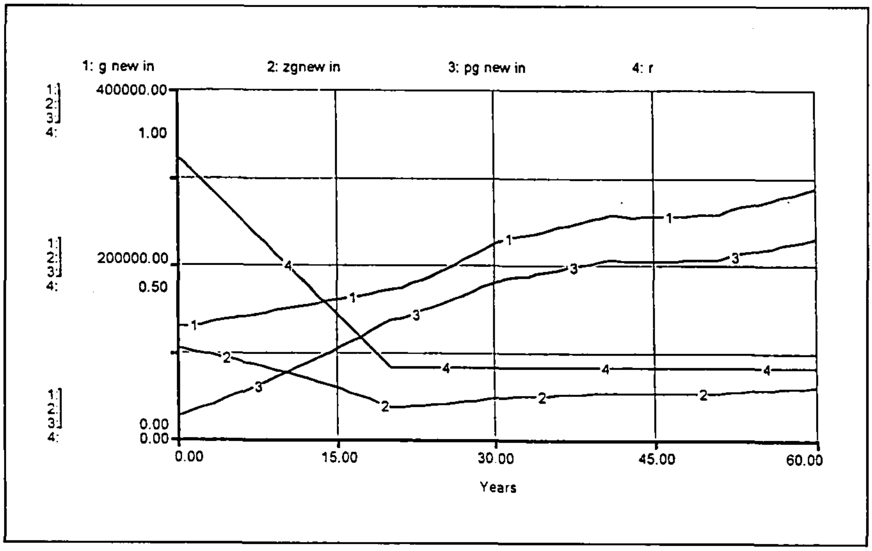

Figure 8. Allocation of the demand over zinc and PVC gutters, preferences shift scenario.

(galv steel w in Figure 7) is decreased because PVC gutters need less galvanized steel for their fastening-pieces, but the use is increased because of the shorter lifetime of gutters. In total the amount of disposed galvanized steel will increase slightly as can be seen in Figure 7. The amount of zinc ore needed is decreased tremendously because of the changed allocation of the gutter demand.

The market share for gutters decreases from 1990 to 2010, beyond which year the allocation variable, r, remains stable, implying a slight increase in the demand for zinc gutters because of a continuously increasing demand for gutters (see Figure 8).

The amount of recycling of zinc is influenced by the decrease of the use of zinc gutters in the first twenty years. The amount of recycling of zinc reacts to the demand for zinc gutters with a time-lag of thirty years. In contrast with the demand for zinc gutters the PVC gutters are used more. After twenty years the amount of PVC which is recycled increases. The costs of meeting the demand rise, because the lifetime of PVC gutters is shorter which means that more gutters are needed. The revenues of used materials are lower because re-used PVC does not yield a revenue. These two effects make the net cost raise, whereas the negative impact on the extraction of materials out of the environment is reduced. The impact of the disposal of materials is twofold: on the one side, the disposal of zinc and galvanized steel is reduced; on the other side, the disposal of PVC is increased.

Results of the Product Charge Scenario (Figure 9)

In the product charge scenario the price of zinc is increased by a charge imposed by the government. Because of the difference in the prices of PVC and zinc gutters the market shares will change. It is assumed that the percentage of zinc gutters in the total demand decreases from 80 percent to 20 percent. As a consequence of this a greater part of the demand for gutters will be met by PVC gutters, which has an impact on the total amount of disposed materials, as in the preferences shift scenario. The impact on the extraction and disposal of materials is roughly the same as in the preferences shift scenario. The demand for gutters shows a more capricious course than in the base and preferences shift scenarios (see Figure 9). From years twenty to thirty the demand increases more strongly than before because the PVC gutters that were demanded in the first ten years are renovated. In the first ten years the share of PVC gutters in the total demand increased strongly. From years thirty to forty the zinc gutters that were demanded in the first ten years, and the PVC gutters that were demanded twenty years ago are renovated. Together with the gutters for new houses is this demand smaller than in the previous ten years? The undulation of the demand over time decreases over time, because the impact of the initial change on the market share decreases over time.

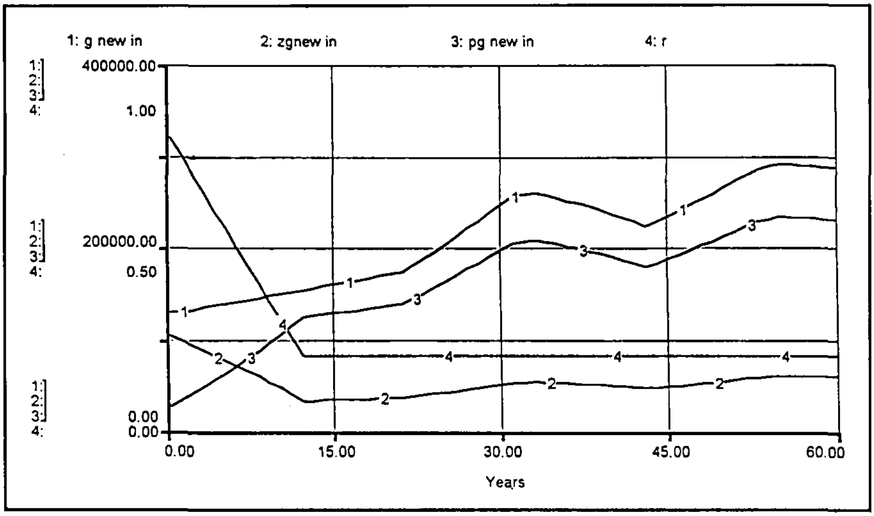

Figure 9. Allocation of the demand over zinc and PVC gutters, product charge scenario.

The costs of meeting the demand are increased because 1) the price for zinc gutters is increased, 2) the PVC gutters have a shorter life span, and 3) used PVC does not have a positive effect on the total costs.

Results of the Recycling Scenario (Figures 10 and 11)

In the recycling scenario the prices for used materials are higher, which implies that the quantities of zinc and PVC recycled increase. This scenario does not have an impact on the demand for gutters. Because of the price increases of used zinc and PVC, the recycling percentages are assumed to increase from 80 to 90 percent for zinc and from 70 to 80 percent for PVC. Less zinc is extracted and less zinc and PVC are disposed, which has a small but positive impact on the environment as can be seen by comparing Figure 5 and 10 (lines 1). The net costs decrease slightly because of the increased prices and amounts of recycled materials.

The quantities of zinc (z recl in for the zinc recycling of zinc gutters of demolished houses, z rec2 in for the zinc recycling of renovated zinc gutters) and PVC (p recl in for the PVC recycling of PVC gutters of demolished houses, p rec 2 in for the PVC recycling of renovated PVC gutters) that are recycled are slightly higher than in the base scenario. The course of the quantities of recycling can be seen in Figure 11.

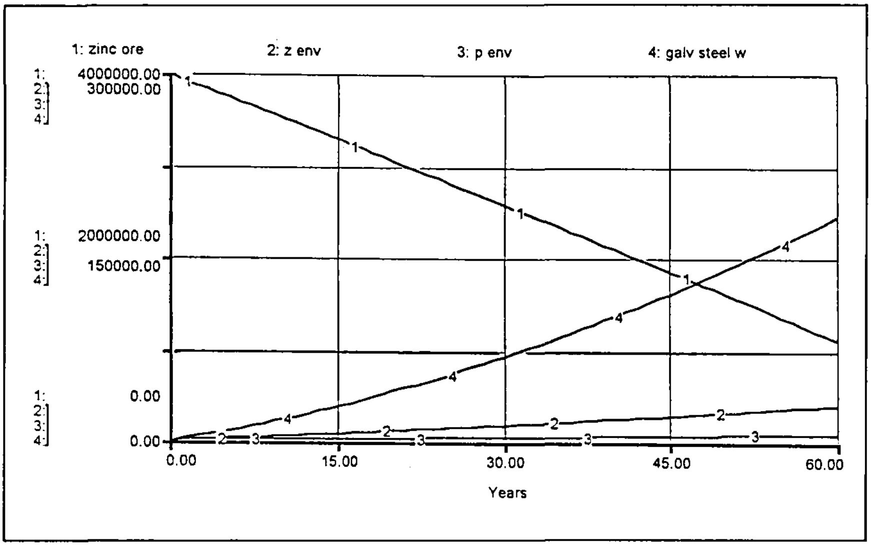

Figure 10. The extraction of and the disposal to the environment, recycling scenario.

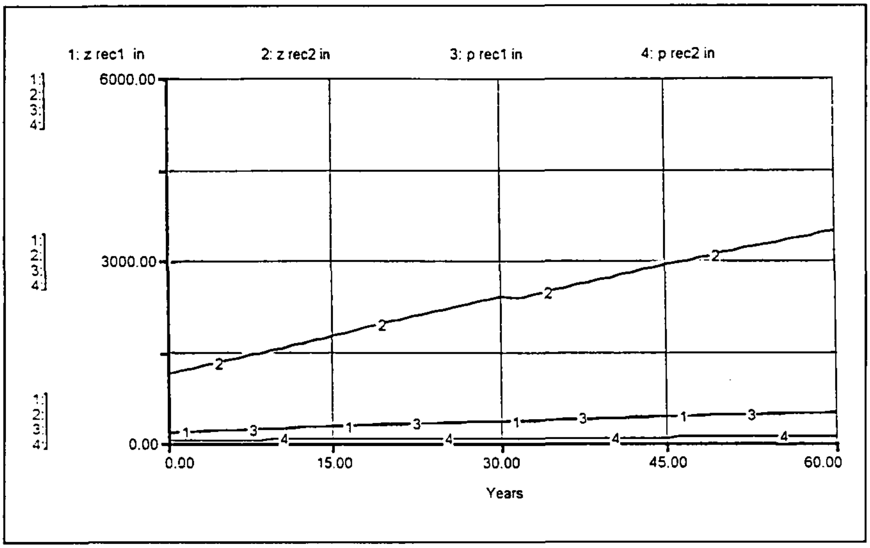

Figure 11. The quantities of zinc and PVC that are recycled recycling scenario.

Results of the Mixed Scenario (Figures 12 and 13)

This scenario combines the product charge and the recycling scenarios. In this scenario the prices of zinc gutters, used zinc, and used PVC are increased. The effects on the environment are slightly better than in the product charge scenario because of the small increase of recycled materials. The allocation of the demand for gutters is equal to the product charge scenario (see Figure 9), while the recycling quantities are slightly different compared with the recycling scenario (see Figure 11). The net costs are slightly lower because of the revenues of selling used materials for recycling purposes. Figure 12 shows the net costs (line 5), the prices of zinc gutters (line 4), PVC gutters (line 1), used zinc (line 3), and used PVC (line 2).

Because of the change in the prices for zinc gutters, used zinc, and used PVC the quantities of zinc that are recycled decrease steeply after thirty years while the quantities of recycled PVC increase after twenty years. Afterwards the quantities of recycled materials show a more stabilized course as can be seen in Figure 13.

8. CONCLUSIONS AND FURTHER RESEARCH

In economic processes the demand for a service can be met by various products consisting of different materials. Materials flow models analyze these products and their environmental aspects from a materials perspective. Most models of materials flows are based on mass balance principles; however, this overlooks the

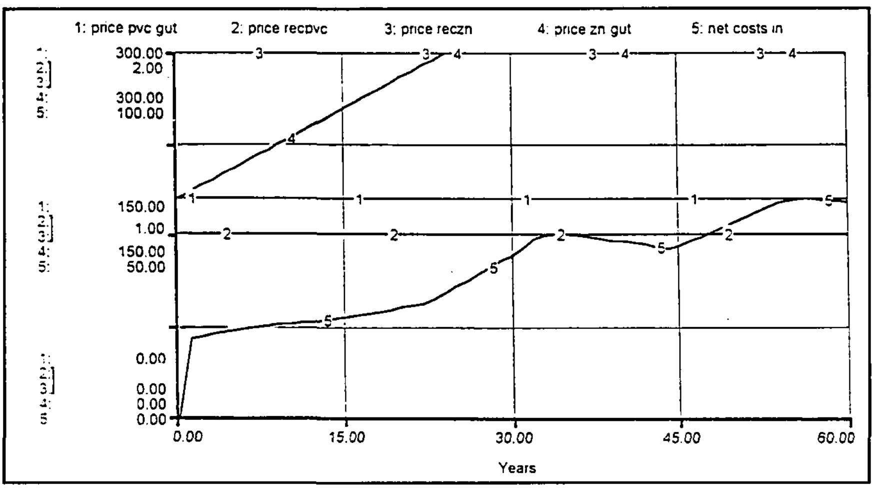

Figure 12. The net costs of meeting the demand for gutters, mixed scenario.

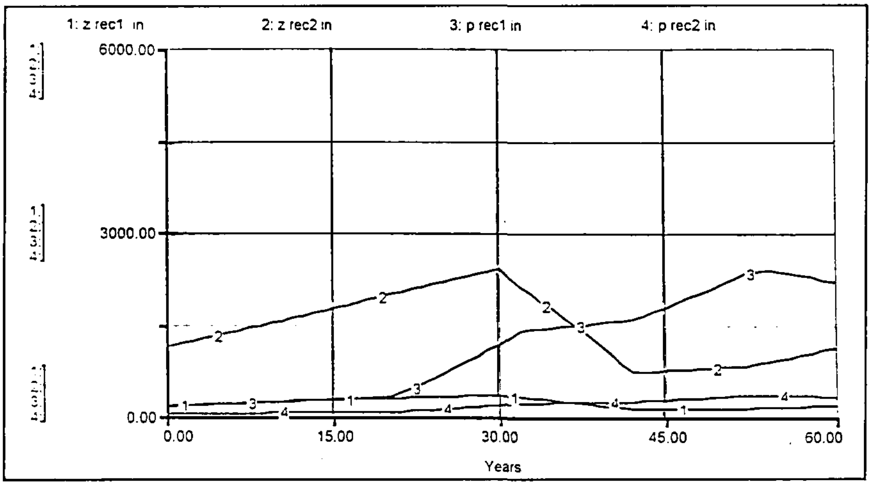

Figure 13. The quantities of zinc and PVC that are recycled, mixed scenario.

role of products and economic forces operating on materials and products. The concept of M-P chains takes into account the links between complementary products and materials and the substitutability between materials and products. Therefore, links between materials and products are considered; although possibly at the price of less rigor. In this article the simple dynamic simulation model for M-P chains for gutters is intended to reflect: 1) the significance of products and processes for the analysis of flows of materials and 2) to track the environmental impact of economic and government policy variables on M-P chains.

The impact of economic and policy variables on chains is important for the materials and product flows through the economy because changes in prices induced by government policies or market forces can alter the flows of materials and products. The use of M-P chains as units of analysis is justified since particular physical as well as economic aspects are incorporated.

A model of a particular M-P chain has been developed based on some characteristics of a system of two alternative products to satisfy a specific need: zinc and PVC gutters to meet the demand for gutters. The environmental impacts of this M-P chain are related to zinc ore depletion and waste flows of zinc, galvanized steel, and PVC into the environment. The economic aspects are limited here to the costs of purchasing and the revenues for used materials.

The scenario simulations show that the impact of prices of zinc gutters and the preferences of consumers for a certain type of gutter may have an important impact on the use of materials. An increase in the prices of used materials can raise the percentages of recycling of these materials. However, the influence of an increase in the price of used zinc is not great because the recycling percentages are high already. A change in preferences for the type of gutter has a significant influence of the use of zinc and PVC.

There are several opportunities to elaborate this model with other economic characteristics, e.g., changes in the costs of collection, recycling, or disposing. Some further research topics are: elaboration of the dynamics of the M-P chains, e.g., regarding technological developments in recycling of galvanized steel; and the extension of the M-P chains with more products or materials, e.g., by taking other zinc products into account. Data availability and the uncertainty about future events may prove to be serious obstacles in using M-P chain models to explore future developments in relation to materials flow. Yet these models present an important opportunity to incorporate some of the main forces driving materials flows.

APPENDIX: The Simulation Model

Submodel for Gutters in Housing

(1) init g_acc = 2660560
Initially the number of gutters in the economy is set at 2660560. This is less than the estimate in [11] but it is more consistent with the estimates of the renovation and demolition of gutters. The stock of gutters equals the stock of last year plus the new gutters minus the gutters in demolished and renovated houses.

(2) g_dem_in = pg_dem_in+zg_dem_in
The total number of demolished gutters is the sum of the demolished PVC- and zinc gutters.

(3) g_ren_in = pg_ren_in+zg_ren_in
The total number of renovated gutters is the sum of the renovated PVC- and zinc gutters.

(4) g_new_in = 75000+g_ren_in
Every year 75000 new gutters are needed for the construction of new houses added to the number of renovated gutters.

Submodel for Zinc Gutters

(5) init zgacc = 2660560*0.8
The initial stock of zinc gutters is 80% of all gutters (see equation 1).

(6) zgnew_in = g_new_in*r
The amount of new zinc gutters are a part, r, of the new gutters.

(7) (i) r = .8
In the base scenario the percentage of the gutter demand which is satisfied by zinc gutters is 80%.

(ii) r = max(0.8–0.03*t,0.2)
In the preference shift scenario the percentage of the gutter demand which is satisfied by zinc gutters is r = max (80–3*t,20)% which means that the part of the demand which is allocated to zinc gutters decreases in time until a certain minimum.

(iii) r = max(0.8–0.01*(price_zn_gut_price_pvc_gut), 0.2)
The percentage of the demand which is satisfied by zinc gutters depends on the prices of both zinc and PVC gutters.

(8) zg_dem_in = if t<31 then (48832+1812*t)*.12 else dummy1*0.12
zg_ren_in = if t<31 then (48832+1812*t)*.88 else dummy1*0.88
dummy1 = delay(zgacc_in,30)
The first 30 years the initial number of zinc gutters is renovated or demolished. The amount of gutters that are renovated in 1990 is derived from [11]. In the following years more zinc gutters are renovated or demolished because the construction of houses has risen from the sixties to the nineties. After 30 years the number of demolished and renovated gutters is set equal to the new gutters with a time-lag of 30 years, i.e., the new gutters of 1990 are demolished or renovated in 2020. The 30 years time-lag is taken as an average lifetime of all gutters [11].

Submodel for PVC Gutters

(9) init pvc_g_acc = 2660560*.2
Initially 20% of the gutters are made from PVC (see equation 1).

(10) init pg_new = 75000*.2
Initially 20% of the new gutters are allocated to PVC.

(11) pg_new_in = g_new_in*(1–r)
A part of the demand for gutters is allocated to PVC.

(12) pg_dem_in = if t<21 then (12208+679.6*t)*.12 else dummy2*0.12
pg_ren_in = if t<21 then (12208+679.6*t)*.88 else dummy2*0.88
dummy2 = delay(pg_acc_in,20)
in the first twenty years the initial amount of PVC gutters is demolished and renovated. The amount of gutters that are renovated in 1990 is derived from [11]. In the following years more zinc gutters are renovated or demolished because the construction of houses has risen from the sixties to the nineties. Afterwards the number of demolished and renovated gutters are set equal to the new PVC gutters of 20 years ago. This 20 years time-lag is equal to the average lifetime of a PVC gutter.

Submodel for Fastening-Pieces

(13) init accfastp = 2660560*.2*0.0168
Initially 20% of the gutters is made from PVC. For every PVC gutter is 16.8 kilograms (0.0168 tonnes)
f galvanized steel needed to make the fastening-pieces.

(14) init accfastz = 2660560*.8.0258
Initially 80% of the gutters is made from zinc. For every zinc gutter is 25.8 kilograms (0.0258 tonnes) of galvanized steel needed to make the fastening-pieces.

(15) accfp_in = g_acc_in*(1–r)*.0168
The number of fastening-pieces of galvanized steel for PVC gutters in the economy depends on demand for PVC gutters. Note that r is the part of gutters which are made from zinc.

(16) gal_w1 = (pg_ren_w_in+pg_sloop_in)*.0168
The quantity of galvanized steel which goes to the environment as waste depends of the number of PVC gutters which are dismissed.

(17) accfz_in = g_acc_in*r*.0258
The number of fastening-pieces of galvanized steel for zinc gutters in the economy depends on demand for zinc gutters. Note that r is the part of gutters which are made from zinc.

(18) gal_w2 = (zgren_w_in+zgsloop_in)*.0258
The quantity of galvanized steel which goes to the environment as waste depends of the number of zinc gutters which are dismissed.

Submodel for Zinc

(19) init new = (75000+72000*.75)*.8*.0296+100
The zinc which is needed for the zinc gutters is produced. The production waste 100 tonnes is included. For one zinc gutter is .0296 ton zinc ore needed.

(20) init zacc = 2660560*0.8*0.296
Initially there are 2660560*0.8*0.0296 tonnes of zinc.

zinc_out = zgnew_in*.0296
The amount of zinc needed for the gutters equal the number of gutters multiplied by the amount of materials in tonnes per gutter.

(22) z_dem_in = zg_dem_in*(.0296-0.00011*30)
The amount of demolished zinc equals the number of demolished zinc gutters multiplied by the amount of materials in tonnes per zinc gutter.

(23) z_ren_in = zg_ren_in*(.0296-0.00011*30)
The amount of renovated zinc equals the number of renovated zinc gutters multiplied by the amount of materials in tonnes per zinc gutter.

(24) (i) z_recl_in = .9*z_dem_in
The amount of recycled zinc from demolition depends on the price of used zinc and the amount of demolition waste. In the base scenario the price of recycled zinc is 1 which makes that 90% of the demolished zinc-waste is recycled.
(ii) z_recl_in = .8+price_reczn-.1
The percentage of zinc-recycling is assumed to be (80+ price of used zinc*10)% for both the demolition and the renovation waste in the recycling-policy scenario.

(25) (i) z_rec2_in = .9*z_ren_in
The amount of recycled zinc from renovation depends on the price of used zinc and the amount of renovation waste. In the base scenario the price of used zinc is 1 which makes that 90% of the renovated zinc-waste is recycled.
(ii) z_rec2_in = .8+price_reczn-.1
The percentage of zinc-recycling is assumed to be (80+price of used zinc*10)% for both the demolition and the renovation waste in the recycling-policy scenario.

(26) rec_out = reczn
The recycled zinc goes directly to the zinc-stock.

(27) zleach_in = .00011*zgacc
Every year a part of the zinc gutters is leached out.

(28) z_env1_in = zleach_in
All the leached zinc goes directly to the environment.

(29) z_env2_in = z_dem_in-z_recl_in
The part of the demolition waste which is not recycled is disposed in the environment.

(30) z_env3_in = z_ren_in-z_rec2_in
The part of the renovation waste which is not recycled is disposed in the environment.

(31) z_env4_in = 100
The production waste is 100 every year.

(32) r (see equation 7)

Submodel for PVC

(33) init p_acc = .0161*0.2*2660560
Initial amount of PVC in economy.

(34) p_rec_out = p_rec
Recycled PVC does not have the same quality as new zinc. It cannot be used for PVC gutters again and therefore it goes to another sector.

(35) (i) p_rec1_in = .7*p_ren_in
The quantity of recycled PVC from renovation depends on the price of used PVC and on the amount of renovated PVC waste. In the base scenario the price of used PVC is 0.

(ii) p_rec1_in = .7+price_recpvc*.1
The percentage of PVC-recycling is assumed to be (70+price of used pvc*10)% for both the demolition and the renovation waste in the recycling-policy-scenario.

(36) (i) p_rec2_in = .7*p_dem_in
The quantity of recycled PVC from demolition of houses depends on the price of used PVC and on the amount of demolished PVC-waste. In the base scenario the price of used PVC is 0.

(ii) p_rec2_in = .7+price_recpvc*.1
The percentage of PVC-recycling is assumed to be (70+price of used pvc*10)% for both the demolition and the renovation waste in the recycling-policy-scenario.

(37) p_dem_in = pg_dem_in*.0161
p_ren_in = pg_ren_in*.0161
p_new_in = pg_new_in*.0161
The amount of PVC gutters in the different stages of the chain can be converted into tonnes by multiplying by 0.0161.

(38) p_env1_in = p_dem_in-p_rec2_in
The part of the demolished PVC-waste which is not recycled, is disposed in the environment.

(39) p_env2_in = p_ren_in-p_rec1_in
the part of the renovated PVC-waste which is not recycled, is disposed in the environment.

Submodel for Ores

(40) init fe_ore = 4000000
Initially the iron-ore stock is arbitrarily set a 4 million tonnes.

(41) init zinc_ore = 4000000
Initially the zinc ore stock is arbitrarily set at 4 million tonnes. Every year zinc is extracted for zinc gutters and for the production of galvanized steel to make two types of fastening-pieces.

(42) fepvc_in = accfp_in*1.44
One ton of galvanized steel for a PVC-fastening piece needs 1.44 tonnes of iron ore.

(43) fezn_in = accfz_in*1.44
One ton of galvanized steel for a zinc-fastening piece needs 1.44 tonnes of iron-ore.

(44) znpvc_in = accfp_in*1.67
One ton of galvanized steel for a PVC-fastening piece needs 1.67 tonnes of zinc ore.

(45) znzn_in = accfz_in*1.67
One ton of galvanized steel for a zinc-fastening piece needs 1.67 tonnes of zinc ore.

(46) zinc_ore_out = (zinc_out-z_rec_out)*22.3
The zinc ore which is used for zinc gutters is the amount of new produced zinc multiplied by the amount of zinc ore needed for one ton of zinc, i.e. 22.3 tonnes.

Submodel for Costs and Prices

(47) net_costs_in = (zgacc_in*price_zn_gut+pg_acc_in*price_pvc_gut-1000*(reczn*price_reczn-p_rec_out*price_recpvc))/1000000
The net costs of satisfying the demand for gutters is equal to the price of zinc gutters multiplied by its demand plus the price of PVC gutters multiplied by its demand minus the revenues of used zinc and used PVC. These revenues are equal to the price of used zinc multiplied by the amount of recycled zinc and the prices of used PVC multiplied by the amount of recycled PVC. The revenues have to be multiplied by 1000 because the price is given per kilogram and the amount in tonnes. The net costs are in million guilders per year which makes that the right side has to be divided by 100000.

(48) price_pvc_gut = 180
In the base case the price of a PVC gutter is 180 guilders and does not change over time [8].

(49) (i) price_recpvc = 0
The price of used PVC is 0 guilders per kilogram.
(ii) price_recpvc = 1
In the recycling and mixed scenario is the price of used PVC 1 guilder per kilogram.

(50) (i) price_reczn = 1
The price of a used zinc is 1 guilder per kilogram (Recycling, maart/april (1994)).
(ii) price_reczn = 2
In the recycling and mixed scenario is the price of used zinc 2 guilders per kilogram.

(51) (i) price_zn_gut = 180
In the base case the price of a zinc gutter is 180 guilders and is assumed to remain stable over time [8].

(ii) price_zn_gut = min(180+charge,300)

In the product charge scenario the price for zinc gutters is initially 180 guilders, but the government imposes a charge which increases the price of a zinc gutter.

charge = min(5*t,120)

the charge will be raised by 5 guilders every year, up to a maximum of 120 [13].

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