

Appendix A. The *WasteTrans* Model

A.1. Overview

The model for the Dutch waste management transition case, i.e. *WasteTrans*, is a system dynamics model, which is developed using Vensim software. The model covers 3 waste management options (i.e. land-filling, incineration, recycle/re-use), and the behaviour of 4 actor groups (i.e. municipalities, waste contractors, government, opinion groups) with respect to these available waste management options. In the following section, we will introduce the basic model structures and formulations that are used to represent change processes regarding the options, as well as regarding the behaviour of the actors.

Following sections introduce the conventions regarding the *stock-flow diagrams*, which are the visual representations of model structure in system dynamics approach, and the abbreviations used in the *WasteTrans* model.

A.2. Stock-flow diagrams

In system dynamics, two main building blocks are used in modelling the system of concern. *Stocks* are briefly accumulating variables that identify the state of the system at a particular time. These stocks are manipulated via instantaneous inflows and outflows, which are referred as *flow* variables.

A simple system regarding atmospheric CO₂ accumulation is presented in the stock-flow representation form in Figure A.1. In this representation, the *stock* variable of the system (*Atm_CO2*) is represented with a rectangular box. The thick arrows with valves pointing to, and emerging from this *stock* variable represent the *flow* variables related to this *stock*. Arrowheads indicate the direction of these flows. According to this representation, inflow to the stock is emissions by fossil fuel usage (*EmsByFossilFuels*), and outflow from the same stock is the diffusion flow (*CO2_Diffusion*). In each time period, magnitude of *EmsByFossilFuel* indicates the amount of CO₂ added to the atmosphere, whereas *CO2_Diffusion* represents the amount flowing out of the atmosphere via diffusion to the oceans. Remaining variables in the figure are called *auxiliary* (or converter) variables and they are used for calculation of flows and defining the links between components of the system (e.g. *FossilFuelUsage*). Finally, curved thin arrows indicate causal relation between two variables in the system. In this simple example, the magnitude of *EmsByFossilFuel* is

formulated as a product of fossil fuels used (*Fossil_Fuel_Used*) and the average emission rate per fossil fuel usage (*Emissions_Per_Fossil_Used*).

System dynamics models corresponds to a set of differential or difference equations, in which *stocks* represent state variables and *flows* represent rates of change. The stock-flow representation of the simple CO₂ example is given in Figure A.1. Differential equations regarding the same system are also given in Equations A.1 through A.3.

$$\frac{dAtm_CO2(t)}{dt} = EmsByFossilFuels(t) - CO2Diffusion(t) \quad [A.1]$$

$$EmsByFossilFuels(t) = EmsPerFossilFuel \times FossilFuelUsage(t) \quad [A.2]$$

$$CO2_Diff(t) = Atm_CO2(t) \times CO2_Diff_Frac \quad [A.3]$$

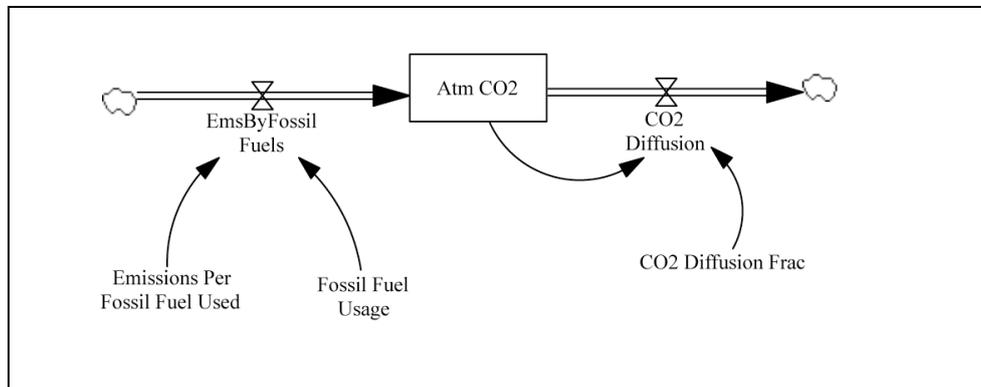


Figure A.1. A simple stock-flow model

A.3. Variable naming convention and abbreviations

Most of the variable names are constructed in a modular manner. The first part of the name of a variable indicates the *option*, or the *actor*-type to which the variable relates. For example, *Land_Capacity* is the variable that represents the installed capacity for landfilling. Similarly, *Reg_Imp_SoilPoll* is the variable that represents the importance of soil pollution for the regulator actors in the model. The variable names can be interpreted in this manner using the abbreviations given below;

Abbreviation	Description
<i>Cap</i>	Capacity
<i>Chg</i>	Change
<i>Del</i>	Delay
<i>Eff</i>	Effect
<i>Imp</i>	Importance
<i>Inc</i>	Incineration
<i>Ini</i>	Initial
<i>Inv</i>	Investment
<i>Inv</i>	Investment
<i>Land</i>	Landfilling
<i>Norm</i>	Normal (i.e. reference condition)
<i>Perc</i>	Perception/perceived
<i>Poll</i>	Pollution

<i>Pract</i>	Practitioner
<i>Prov</i>	Provider
<i>Reg</i>	Regulator
<i>Sup</i>	Support

A.4. Options

As mentioned earlier, the model covers three major options for waste management; landfilling, incineration, and recycle/re-use. These options are primarily characterized by their performance in soil pollution (i.e. pollutant released to soil per unit of waste processed), air pollution, and space requirements. All these properties are considered as mainly related to the technological nature of the options, and they are modelled to be dynamic. The model structure used for each property of each option is identical, but they only differ in the values of parameters, which determine the dynamics of development. Therefore, we only discuss the structure used for soil pollution performance of the landfilling option as an example. Stock-flow diagram related to the technological development in the soil pollution performance of landfilling is given in Figure A.2.

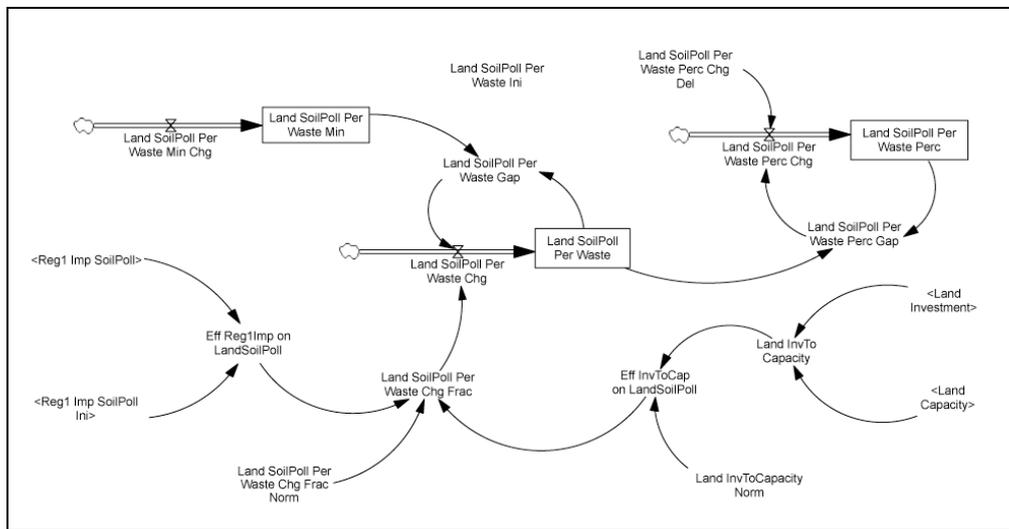


Figure A.2. Option development structure

The best feasible level of the soil pollution performance is represented by the variable *Land_SoilPoll_Per_Waste_Min*. This variable changes over time representing an exogenous property development mechanism. However, an improvement in the best feasible level does not automatically correspond to an improvement in the soil pollution performance of the landfilling practice in the system (*Land_SoilPoll_Per_Waste*) since the existing capacity uses old technology and/or practices. The change in *Land_SoilPoll_Per_Waste* is dependent first of all on the gap between the current performance level, and the best feasible one; i.e. *Land_SoilPoll_Per_Waste_Gap*. Two other factors also influence the rate of development. One of them is the regulatory push, which is represented by the current importance of the soil pollution for the regulator compared to its reference level (i.e. initial level). Second one is the ratio of investment funds allocated to landfilling by providers to the available capacity. A high ratio indicates a higher possibility of

technical improvement through new investments. The equations used for the aforementioned option development process are given below¹;

$$\frac{dOpt_Prop(t)}{dt} = Opt_Prop_Chg(t) \quad [A.4]$$

$$Opt_Prop_Chg(t) = Opt_Prop_Gap(t) \times Opt_Prop_Chg_Frac(t) \quad [A.5]$$

$$Opt_Prop_Gap(t) = Opt_Prop_Min(t) - Opt_Prop(t) \quad [A.6]$$

$$Opt_Prop_Chg_Frac(t) = Opt_Prop_Chg_Frac_Norm \times f(t) \times g(t) \quad [A.7]$$

$$f(t) = effectIncToCap\left(\frac{Opt_InvToCapacity(t)}{Opt_InvToCapacity(0)}\right) \quad [A.8]$$

$$g(t) = effectRegImp\left(\frac{RegImp_Prop(t)}{RegImp_Prop(0)}\right) \quad [A.9]$$

effectIncToCap(.) and *effectRegImp(.)* are table functions (graphical functions) specified using the GRAPH interface of Vensim software, which is used to specify non-linear interactions between variables. These functions are given below.

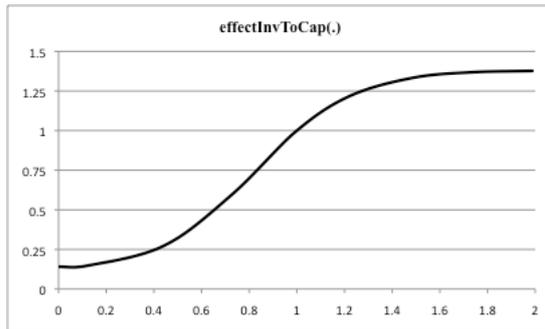


Figure A.3. effectIncToCap(.) function

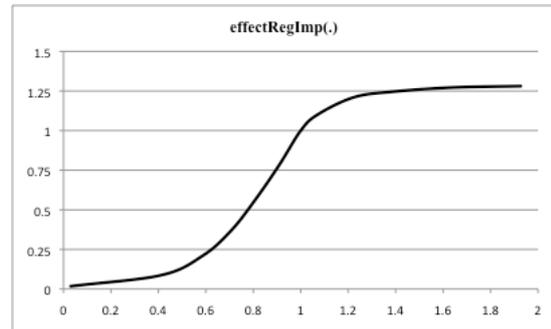


Figure A.4. effectRegImp(.) function

A.5. Actors

The key model structure in *WasteTrans* related to the actors is related to their ‘support’ levels for the available options. The concept of ‘support’ corresponds to different things for different actor groups. For the municipalities (i.e. practitioners), the level of support for an option corresponds to the percentage of waste the municipality plans to manage through that option. For the waste contractors (i.e. providers), it corresponds to the percentage of capacity investments to be allocated to the option. For the government (i.e. regulator), it is the target level waste percentage to be managed through the option. The support-shift structures used for the actor groups are structurally identical, and mainly differ in parameter values that represent the possible pace of support shift. Below we discuss the support-shift structure on the example of provider actors (Figure A.5);

¹ For convenience, Opt (i.e. option) stands for ‘Land’, and Prop (i.e. property) stands for ‘SoilPollPerWaste’ in this particular example.

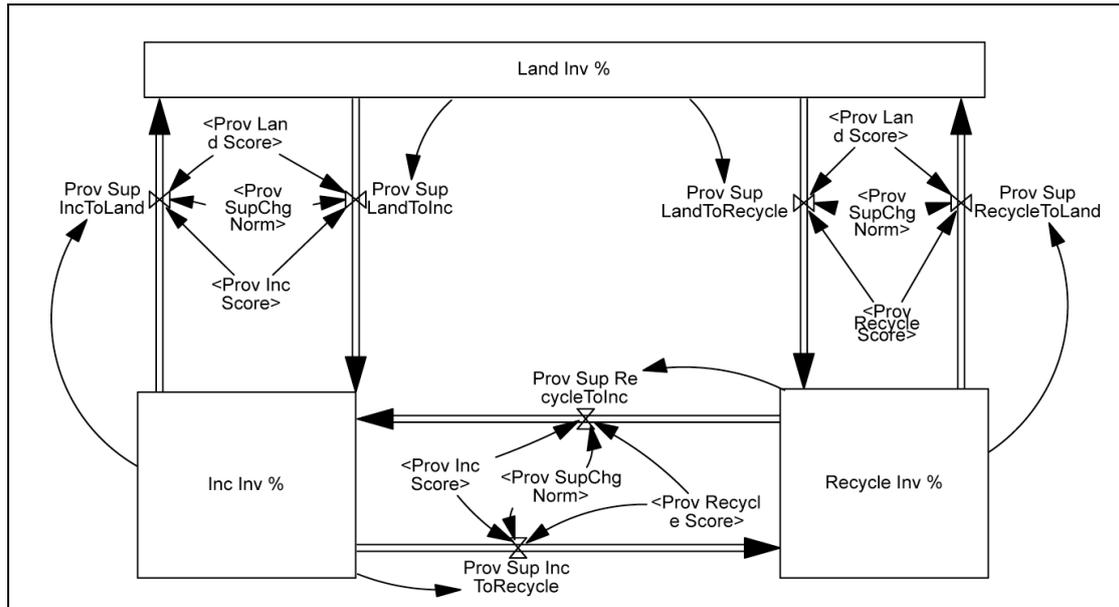


Figure A.5. Support-shift structure for the provider-type of actors

The actors are conceptualized as shifting their support between the available options in the model. In doing so, it is assumed that the waste contractors are committed to their former course of investment behaviour, which also includes investments made to replace depreciating capacity. In that respect, they change their investment behaviour in a gradual manner, instead of a radical history-independent manner. According to the used model structure, the change in the investment percentage to incineration, for example, increases by shifting support from the other two options, and decreases by shifting support to the other two options.

$$\frac{dIncInv\%(t)}{dt} = s_{Recycle,Inc}(t) + s_{Land,Inc}(t) - s_{Inc,Recycle}(t) - s_{Inc,Land}(t) \quad [A.10]$$

where;

$s_{A,B}(t)$: *Prov_Sup_AToB* variable in the stock - flow diagram

An actor's shifting of support from one option to another is dependent on how the actor assesses these options; the actor will shift support from the option with relatively lower assessment score to the one with a higher assessment score. Based on this logic, the individual support-shift flows in Figure A.5 are formulated as follows;

$$s_{A,B}(t) = H(V_B(t) - V_A(t))[\gamma(V_B(t) - V_A(t))AInv\%(t)] \quad [A.11]$$

$$\text{where } H(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad [A.12]$$

According to this formulation, there is a support shift from option A to option B only if the actor assesses the option B to be superior to the option A. The pace of support shift is dependent on the difference in the assessment of the options; if the difference of the actor's assessments for the options is low, the pace of support shift is also low. Additionally, the shift of support is proportional to the current level of support for the losing option. γ stands for the reference level of support shift pace. The key variables

in this formulation are the assessment scores (i.e. $V_A(t)$), which will be discussed below.

The actors consider multiple issues, such as their soil and air pollution performance, while attributing an assessment score to an option. In doing so, a set of weights is used to represent the relative importance of a certain issue for the actor. Using these weights (i.e. $\lambda(.)$), the total assessment score of an option is calculated as follows;

$$V_A(t) = \sum_j \lambda_j(t)v(\hat{x}_{A,j}) \quad [A.13]$$

$\hat{x}_{i,j}$ is the relative performance of the option i (e.g. landfilling) in the issue j (e.g. soil pollution), and this is calculated by comparing the performance of an option with the best performance among the available options (Equation A.14). It is important to note that, since it is the relative performance of an option that matters, an option's assessment by the actors may worsen if the best available performance in an issue improves.

$$\hat{x}_{A,j} = \frac{x_{A,j}}{\min_i(x_{i,j})}, \quad i = A, B, C... \quad [A.14]$$

$v(.)$ is the component value function, which converts the relative performance of an option with regard to an issue into a scalar value in the range of $[0,5]$. If the option performs best in an issue, the component value function returns 5. If the option is performing very poorly compared to the best performance available it is attributed 0. The component value function incorporates a level of status quo-seeking tendency, since the value attributed to an option starts decreasing only when it performs significantly worse than the best option. Even when a better option is available for the actor, the actor has a tendency to value this new option and the actor's current choice very closely, as long as the new one does not outperform the current choice of the actor.

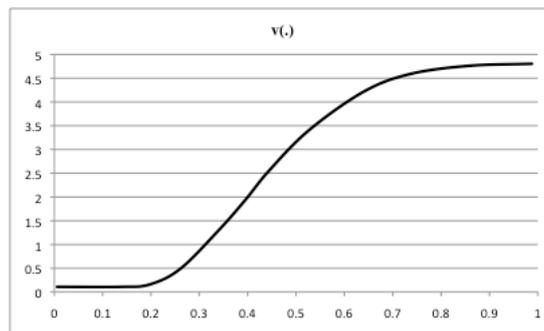


Figure A.6. Component value function

The importance of the issues for the actors (i.e. $\lambda(.)$) is also time-dependent in the model. Figure A.7 provides a sample structure for demonstrating the way importance of an issue is changing in the model for an actor. The selected case is about the importance of air pollution issue for the practitioner-type of actors. The driver of change is the recent air pollutant emission level relative to what it was in the past (i.e. $AirPollEmissions_Rel$). However, an increase in the emission levels does not induce

an immediate jump in the importance of the air pollution issue for the actors. First of all, internalization of the problem, and reflecting it to the preferences of the actor is assumed to take some time for the actors. Therefore, an increase in the emissions yields a change in the importance of the issue (i.e. *Pract_Imp_AirPoll*) in a gradual manner, and after an importance change delay. The equation formulations used for the importance change process are given in Equations A.15 through A.17.

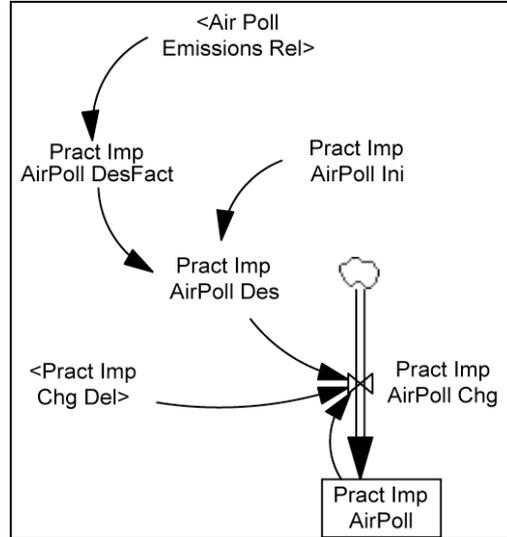


Figure A.7. A section from the preference change structure

$$\frac{dImpAirPoll(t)}{dt} = \frac{ImpAirPoll_Des(t) - ImpAirPoll(t - dt)}{Imp_Chg_Del} \quad [A.15]$$

$$ImpAirPoll_Des(t) = ImpAirPoll_Ini \times ImpAirPoll_DesFact(t) \quad [A.16]$$

$$ImpAirPoll_DesFact(t) = h\left(\frac{AirPoll_Emissions(t)}{AirPoll_Emissions(0)}\right) \quad [A.17]$$

A.6. Overall system performance

The waste allocation decisions of the municipalities are the primary drivers of waste-related pollution performance of the Dutch system in the model. The total amount of waste to be handled by the municipalities is introduced as an exogenous, time-dependent variable to the model. It is assumed that the waste generation will follow the pattern observed during the 1985-2003 period. The following function, which is calibrated in order to get the best fit to the 1985-2003 data series, is used to represent the total waste generation (in megatons);

$$Waste_Generated(t) = 31.821 + 0.9593t \quad [A.18]$$

The municipalities' allocation of this total waste to the available options determines the amount of waste generated via each waste management option. The dynamics of pollution levels are represented with very simple structures that represent the basic accumulation and decay dynamics related to pollutants in the model. For the soil pollution case (Figure A.8), the amount of pollutants released to soil (i.e. *SoilPollInflow*) is the sum of pollutants from waste managed through all three options. The decay of the pollutants in the soil is represented with a second-order material

delay structure. Following the release of pollutants to the soil in their original form, the first decay process represents the processes such as leaching and diffusion of the pollutants into the soil. In other words, pollutants change form, but still in the system. The decay of this latter form of pollutants correspond to the second outflow in the given stock-flow diagram (i.e. *SoilPoll2_Diff*).

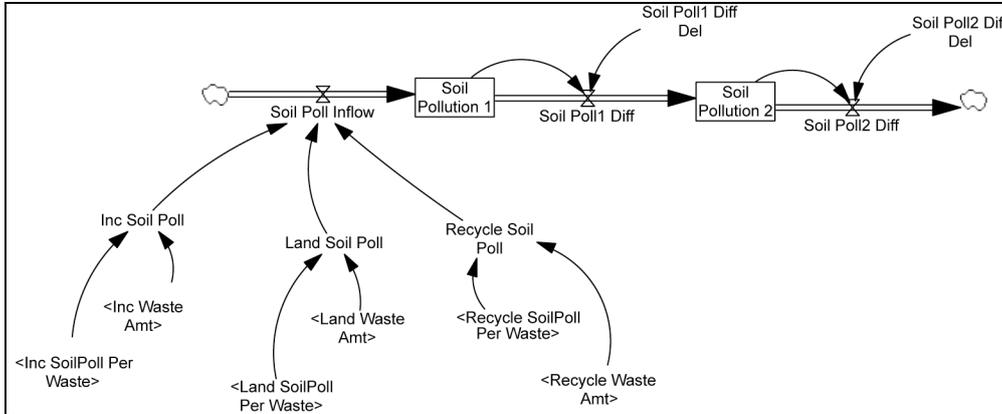


Figure A.8. Stock-flow diagram related to soil pollutions

A very similar stock-flow structure is used for the air pollution case (Figure A.9). Total emission is the result of emissions caused via each waste management option, which is determined by the total amount of waste managed via the option and the air pollution emitted per unit amount of waste. Differing from the soil pollution case, air pollution diffuses much faster when it is considered at the regional level. Due to trans-boundary atmospheric flows, the air pollution levels experienced regionally in the Netherlands can fall much faster compared to the decay of soil pollutants. Additionally, transformation of the air pollutants into a second form as in the case of leaching of soil pollutants is not considered. In that respect, a first-order material delay structure is used to capture the probable dynamics of aggregate regional air pollution levels.

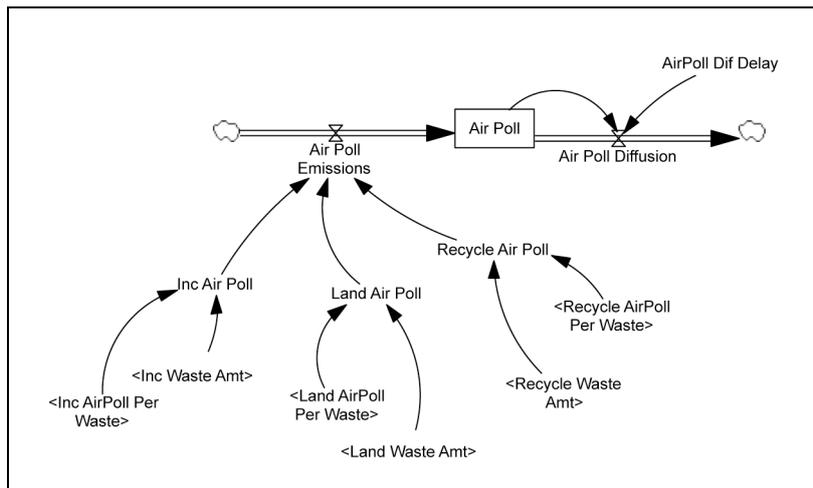


Figure A.9. Stock-flow diagram related to air pollution

A.7. Sensitivity runs

A set of extensive sensitivity runs have been conducted in order to evaluate the robustness of the simulated system behaviour to changes in some uncertain variables. These sensitivity runs are conducted using the integral sensitivity analysis features of the Vensim software. Briefly, the analysis is conducted as follows;

- A set of variables whose initial values carry some level of uncertainty is identified
- Plausible value ranges are defined for each variable
- In each sensitivity run, variables are initialized according to a value randomly sampled from their plausible ranges. Uniform distributions are used in sampling. Although the sampling is done independently for each variable, the consistency of the sampled variables with the qualitative data is preserved. For example, *space* was a more important issue for the government in '70s than the *air pollution*. Therefore, in the sensitivity runs, the initial importance of *air pollution* cannot be higher than the *space* issue. This is what is meant by 'preserving the consistency with the qualitative information'.
- The model is initialized using these randomly sampled values, and it is run.
- The procedure is repeated 1000 times.
- The resulting 1000 output curves are summarized in a single graph, which shows behaviour envelopes. For example, 50% envelope indicates that 500 of the simulations resulted in a behaviour curve that resides in that envelope.

a. Sensitivity to initial importance values

In this experiment the selected set of variables are related to the initial values for the importance of different issues for the regulator actor. The selected variables, and the plausible ranges for these variables are given in Table A.1. The results of the sensitivity runs are given in Figure A.10 and A.11, which show percentage of waste managed through landfilling and incineration, respectively.

Table A.1. Parameter ranges in the sensitivity run

Variable	Base Version	Min	Max
<i>Reg Imp AirPoll Ini</i>	1	0.5	1.5
<i>Reg Imp PubSup Ini</i>	1.5	0.0	3.0
<i>Reg Imp SoilPoll Ini</i>	1	0.5	1.5
<i>Reg Imp Space Ini</i>	2	1.5	3.0

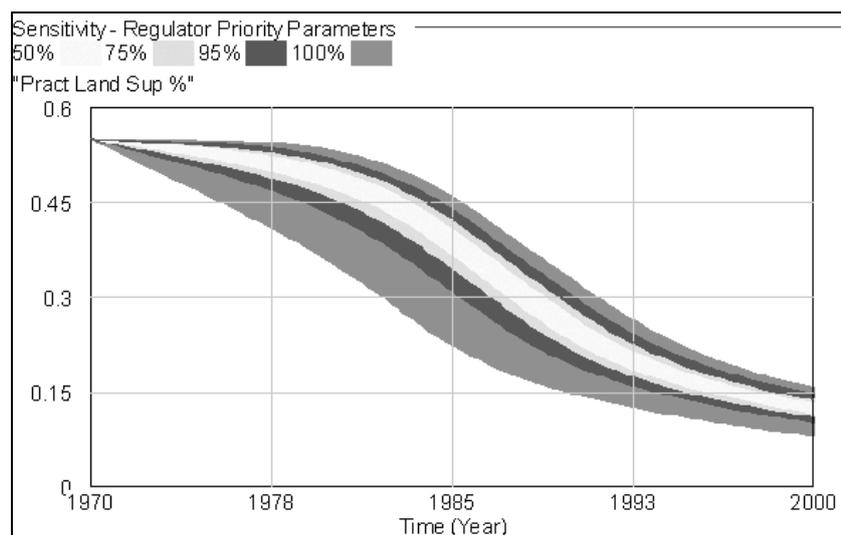


Figure A.10. Share of landfilling in the sensitivity run

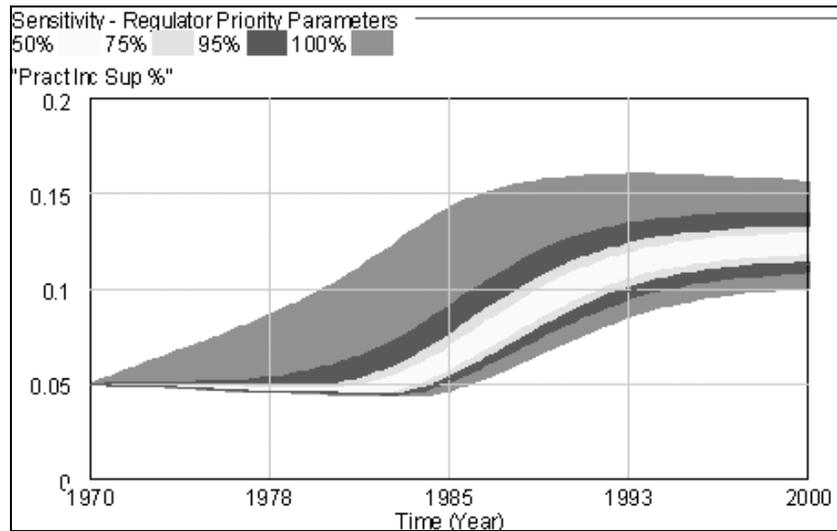


Figure A.11. Share of incineration in the sensitivity run

b. Sensitivity to pace of priority change process

In this experiment the selected set of variables are related to the time it takes for the actors to update their preference (i.e. alter the importance of an issue). The selected variables, and the plausible ranges for these variables are given in Table A.2. The results of the sensitivity runs are given in Figure A.12 and A.13, which show percentage of waste managed through landfilling and incineration, respectively.

Table A.2. Parameter ranges in the sensitivity run

Variable	Base version	Min	Max
<i>Pract Imp Chg Del</i>	10	5	15
<i>Reg Imp Chg Del</i>	7	5	15
<i>Pub Imp Chg Del</i>	7	5	15

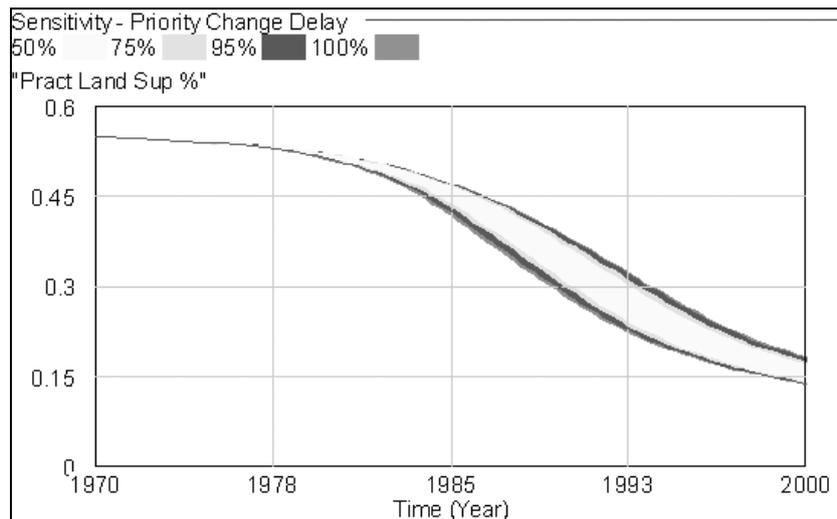


Figure A.12. Share of landfilling in the sensitivity run

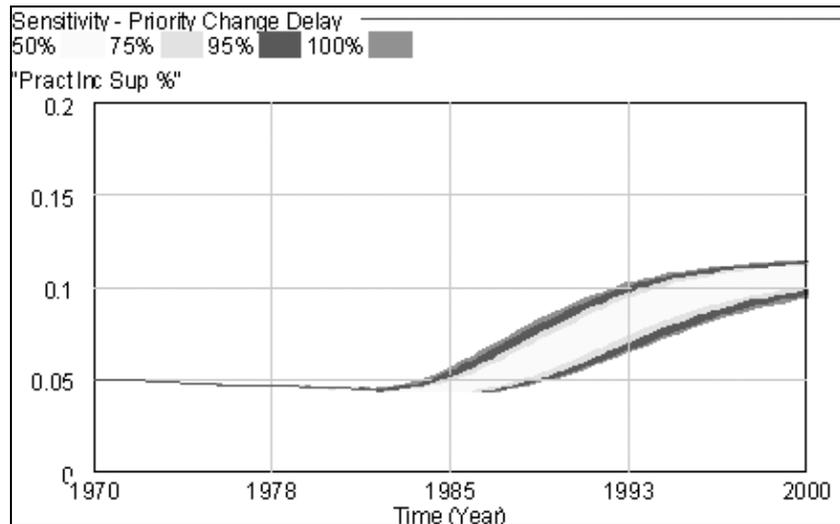


Figure A.13. Share of incineration in the sensitivity run

c. Sensitivity to air pollution performance of the options

In this experiment the selected set of variables are related to the initial values for the air pollution performance of the options (i.e. pollutant emitted per Mton waste processed). The selected variables, and the plausible ranges for these variables are given in Table A.3. The results of the sensitivity runs are given in Figure A.14 and A.15, which show percentage of waste managed through landfilling and incineration, respectively.

Table A.3. Parameter ranges in the sensitivity run

Variable	Base version	Min	Max
<i>Land AirPoll Per Waste Ini</i>	0.6	0.0	2.0
<i>Inc AirPoll Per Waste Ini</i>	3.0	0.0	4.0
<i>Recycle AirPoll Per Waste Ini</i>	0.2	0.0	2.0

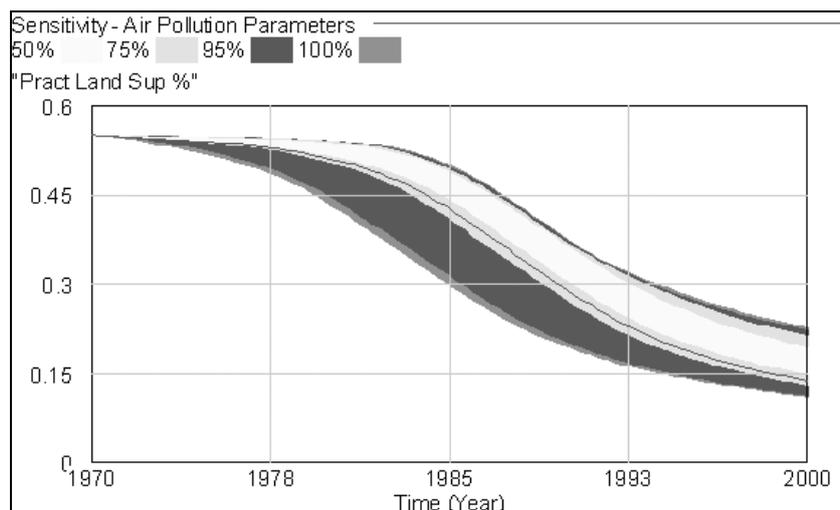


Figure A.14. Share of landfilling in the sensitivity run

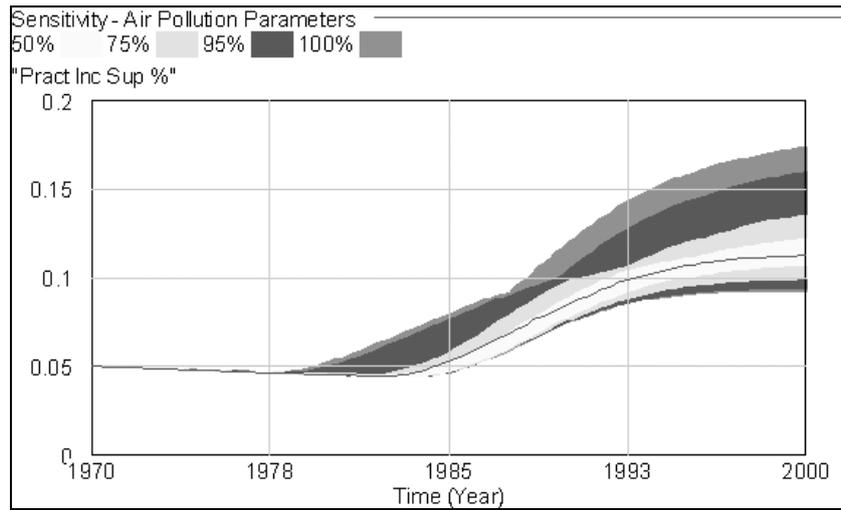


Figure A.15. Share of incineration in the sensitivity run