Chapter 2: An analysis of Household Waste Management Policy using System Dynamics Modelling

Abstract

This paper analyses the Flemish household waste management policy. Based on historical data from the period 1991-2006, literature reviews and interviews, both mathematical and descriptive relationships are derived that describe Flemish waste collection, re-use, recycling and disposal behaviour. This provides insights into how Gross Domestic Product (GDP), population and selective collection behaviour have influenced household waste production and collection over time. These relationships are used to model the dynamic relationships underlying household waste management in Flanders by using a System Dynamics (SD) modelling approach. Where most SD models in literature are conceptual and descriptive, in this article a real-life case with both correlational and descriptive relationships is modelled for Flanders, a European region with an outstanding waste management track record. This model is used to evaluate the current Flemish household waste management policy based on the principles of the waste hierarchy, also referred as the Lansink ranking. The results show that Flemish household waste targets up till 2015 can be achieved by the current waste policy measures. It also shows the sensitivity of some key policy parameters such as prevention and re-use. Given the general nature of the model and its limited data requirements, the authors believe that the approach in this model can also assist waste policy makers in other regions or countries to meet their policy targets by simulating the effect of their current and potential household waste policy measures.

1 This paper has been co-authored by Wout Dullaert, Institute of Transport and Maritime Management Antwerp (ITMMA), Antwerp, Belgium; Antwerp Maritime Academy, Antwerp, Belgium and has been published in 2011 in Waste Management & Research:

1. Introduction

Traditionally, municipal solid waste (MSW) has been regarded as an unwanted product to be disposed off. For more than a decade, there has been increasing recognition in Western economies that discarded items are resources awaiting reclamation for their economic value (see e.g. Louis 2004). In Europe, management of MSW and more specifically the reduction of the amount of waste going to landfills have been significantly influenced by the EU directives 1994/62/EC (amended by 2004/12/EC) and 1999/31/EC. More recently, the EU directive 2006/12/EC forces the European member states to establish concrete plans for waste management in order to achieve the European waste targets. Other important EU directives regulating waste are 2003/108/EC on electrical and electronic equipment, 2006/66/EC on batteries and accumulators and waste batteries and accumulators and 2000/76/EC on the incineration of waste. The EU 2020 climate targets (European Commission, 2008 a & b) create an additional incentive for effective waste management and energy recuperation. Awareness is also increasing in the rapidly developing Asian countries, partially because of the immense growth in waste production but also because of the changed composition of waste in terms of plastics and paper, reflecting an improved standard of living. In the longer term, increasing energy and raw material prices reinforce the interest in value recovery.

Broadly speaking, value recovery from municipal solid waste consists of reuse, recycling or energy recuperation. Golueke and Diaz (1991) define reclamation for reuse as consisting of refurbishing or other upgrading without significantly altering original form and composition (e.g. re-using glass bottles). Recycling on the other hand, involves processing (physical, thermal or biological) discarded items into raw material to be used for manufacturing new products, i.e. resources in the manufacturing of "new" products. Energy recuperation from incineration of materials waste is not new. Louis (2004) reports on waste-to-energy facilities being built at the end of the 19th century in the US, but contrary to the situation in the distant past, waste-to-energy has now become economically viable. Waste-to-energy includes landfill gas collection, incineration with energy recuperation (especially for high caloric wastes), anaerobic digestion with green energy valorisation during the pre-treatment of compost and the production of biodiesel derived from vegetable oil or animal fat (Andries and Loncke, 2008).

Clearly reuse, recycling and waste-to-energy can present alternative uses for the same type of waste and the option with the lowest overall (social) cost in collection and treatment combined with the value obtained from selling the recovered materials should be chosen. In this trade off the influence on the reduction of green house gases should also be taken into account. To assist governments in prioritizing their overall waste management policy, the European Commission advocates the revised Lansink ranking which prefers (i) prevention over (ii) re-use, recycling or incineration with energy recuperation and (iii) incineration or landfill (EU Directive 2006/12/EC).

The actual design of solid waste management systems can be supported by decision support systems. Some of these decision support systems are linear or nonlinear programming models that analyse the waste management system for single time periods (in most cases years).
These waste management systems are described by (non)linear equations. The objective function consists most often of the minimization of the total annual cost of the waste management system under consideration. Such solid waste management models are e.g. used in Sweden (Ljunggren, 2000) using a single period linear programming model and in Canada (Vaillancourt and Waaub, 2002) using a sophisticated mixed integer linear programming model or Wu et al. (2006) using an interval nonlinear programming model. Other objective functions can also be selected such as maximizing energy recuperation, minimizing greenhouse emissions, etc. Constraints can be defined for e.g. waste disposal capacity, recovery goals, emission restriction etc. A multi-objective approach (economics, noise control, air pollution and traffic congestion limitation) using mixed integer programming approach for assessing the long-term optimal waste management solution is described by Chang & Wang (1996). The developed model was applied to a case study in the city of Kaohsiung in Taiwan.

Another type of model calculates in a simple spreadsheet the environmental impact and economic value of waste throughout its entire life cycle (a so-called Life Cycle Analysis, LCA) starting from waste as ‘raw’ material input for comparing different options for managing municipal solid waste treatment systems. Examples of this approach are used for assisting waste management system decision makers in Spain in the region of Pamplona (Wilson, 2002) and the region of Asturias (Rodriguez-Iglesias et al., 2003). LCA can also be integrated in supply chain models, which are commonly focused on cost minimization. Krikke et al. (2003) present a model wherein the product design and product manufacturing is optimized both in terms of cost and environmental impact.

The aforementioned decision support models offer a static optimization for selecting the best municipal solid waste treatment system. However, when evaluating waste management policy over time, they all share the same shortcoming in ignoring the dynamic nature of waste management systems. There is a specific need for assessing dynamic waste management systems over a longer period of time since the focus on municipal waste management could shift due to e.g. changed collective selection behaviour, objectives for environment, waste and energy, etc. Municipal waste policy makers therefore require a comprehensive model to assist them in evaluating their current and future municipal waste management policies. System Dynamics (SD) offers an interesting modelling approach because it can comprehensively model the dynamic behaviour between all processes and actors involved. Simulation is the most commonly used technique to study the effect of different factors on the performance of a closed-loop chain (Ilgin and Gupta, 2010).

System Dynamics allows for modelling feedback loops, time delays and both linear and nonlinear interactions between the processes and actors involved in the integrated waste management in countries or regions. SD models have, amongst others been used for examining the evolution of the waste management system in the Netherlands since 1970 (Yücel and Miluska Chiong Meza, 2008) and for studying the potential and systemic consequences of various structural and policy alternatives for a sustainable urban solid waste management system in Madras, India (Sudhir et al., 1997). Georgiadis & Vlachos (2004) present a general conceptual SD model for evaluating both the effect of the green image of
products on demand and on the local government’s waste management policy for product recovery. SD models can also be used for assessing real-world municipal solid waste closed-loop supply chain models. Georgiadis & Besiou (2008) e.g. developed a SD model for a single producer, single closed-loop supply chain with recycling activities that was tested against a particular real-world application of electronic and electrical equipment in the municipality of Kozani in Greece. This model is extended by Georgiadis & Besiou (2010) with the economical dimensions of sustainability and with a broader number of characteristics for describing the environmental sustainability strategies and the operational features of the closed-loop supply chain.

In this paper, System Dynamics (SD) methodology is used to develop a model that is based on both historical data and dynamic relationships between important variables for assessing the dynamic behaviour of household waste management. Because historical data is available for the problem under consideration, also a Discrete Event Simulation (DES) could have been used. It is a well-known fact that many problems can be modeled with either approach and can produce similar results. Therefore, the choice for SD or DES mainly depends on the needs and interests of the decision maker (Sweetser, 1999). We opted for SD in this paper since this technique is better capable of representing the non-linear human selective waste collection behavior. Moreover, SD better depicts the causal loops of the dynamic system state behavior of the municipal waste process for decision makers. The SD model presented is a global closed-loop materials model, extended with the effect of waste-to-energy recuperation. The main objective of this paper is twofold: (i) develop a comprehensive model that encompasses the dynamic relationships in waste collection, prevention, re-use and recycling and waste disposal in Flanders and (ii) apply this model to real-life data to assess the dynamic effects of various waste management policy plans for obtaining the waste management policy targets of the Flemish government. Flanders, the northern part of Belgium, has a leading position in selective municipal waste collection in Europe (Braekevelt et al., 2008). It has detailed statistical information publicly available to provide the necessary inputs for developing the model. Since the household waste management processes in developed countries are quite common, the model set-up can be easily applied to other regions and countries.

The remainder of this paper is structured as follows. First the household waste management policy of Flanders is discussed together with the achievements on waste collection and disposal since 1991. Before analysing the dynamic behaviour of the Flemish household waste management policy over the past two decades the closed-loop supply chain with both material and energy recovery will be described. Historical data on waste management collection and disposal in Flanders is then analysed and mathematical relationships are derived to build a dynamic simulation tool. The model is used to evaluate waste management policy scenarios that are discussed. Finally, conclusions and suggestions for further research are presented.
2. Household waste policy in Flanders

During the last 25 years, Flanders has built up a well-organized waste management system. Starting without any form of waste management policy, Flanders has shifted towards an integrated waste management policy with respect to products, raw materials, climate and energy policy. The waste management practices of Flanders actually belong to the best-in-class examples in Europe (Braekevelt et al., 2008) and are well documented, making them an interesting case study.

The municipal solid waste that is discussed in this paper concerns “household waste”. This term is defined in the Waste Decree (Decree of 2 July 1981 concerning the prevention and management of waste). VLAREA (Decision of the Flemish government of 5 December 2003 to lay down Flemish regulations in relation to waste prevention and management) (VLAREA, 2008) supplements the definition. According to article 2.1.1. of VLAREA, the term household waste is used to refer to waste that has arisen through the normal operation of a private household (e.g. green waste, packaging waste, white goods waste). Household waste also includes some types of waste which are equated to household waste such as street and road-sweeping refuse originating from maintenance by municipal services, market waste, beach waste and some parts of paper waste (newspapers, printed advertising material, etc.).

To execute the waste management policy, a Household Waste Implementation Plan has been made by OVAM, the Public Waste Agency of Flanders (Braekevelt et al., 2008). The most recent version is dated 7 January 2008 and will last until 2015 unless it is replaced earlier by an updated version. This plan is part of the Flemish Waste Management Policy and complies with the aforementioned European directives.

Flanders’ objective is to build its Waste Management Policy on the principles of sustainable development. Sustainable development is defined as “development that meets the needs of the present without comprising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). For Flanders the sustainable development policy encompasses targets for the environment, economic growth and social development, all of which have to be in harmony with each other. It also wants to uncouple the production of waste from increasing consumption.

Sustainable development is founded on sustainable resource management of materials and energy. The final target is to preserve primary raw materials and the environment for future generations. The principles of sustainable materials and waste management are formulated in the reviewed Household Waste Implementation Plan of 2008 as follows: minimized use of exhaustible primary raw material, optimal use of renewable energy sources, maximized prevention of waste materials, maximized use of waste materials as secondary raw materials and minimized environmental impact during the processing of waste materials.

The ambitious target of this plan is for Flanders to have less than 150 kg non-selective collected waste per capita by 2010. This objective remains unchanged until 2015. This is an ambitious target as the increasing number of smaller households, increasing consumption and
the reduction of the average life cycle of products, increases the production of waste materials.

Nevertheless, the Waste Management Policy seems to be proving effective in reaching this objective since the non-selective collected waste per capita has been equal or less than 160 kg since 2003. The target of 150 kg can be achieved by increasing waste prevention (e.g. reduction of packaging, expansion of composting at home) and increasing the re-use of used goods sold by used goods depots.

Apart from its objectives on waste prevention and recycling, Flanders wants to maintain its good performance in terms of landfill of household waste. Landfill is at the bottom of the waste hierarchy and the policy ambition is to exclude landfill for household waste in 2015.

In the reviewed Household Waste Implementation Plan of 2008 (Braekevelt et al., 2008) the four waste management targets are:

**Target 1:** Sustainable consumption has to increase by increased sustainable innovation focused on developing products that can close the materials loop.

**Target 2:** The total amount of household waste becomes uncoupled from increasing consumption. This is reflected in the target that household waste production per capita may not increase beyond the 2000 level of 560 kg waste per capita per year.

**Target 3:** The fraction of non-selective household waste that is removed forever from the materials loop by e.g. incineration or landfill decreases to the level of maximum 150 kg per capita per year in 2010 and remains steady at this level until 2015.

**Target 4:** The fraction of household waste that has to be disposed of, will be processed according to the waste disposal hierarchy where re-use, recycling and incineration with energy recuperation is preferred over landfill.

These targets can be achieved by many initiatives as specified in the reviewed Household Waste Implementation Plan of 2008. Because the impact of many initiatives will vary over time until 2015 and since the impact of many initiatives has to be estimated, a dynamic modelling approach can be a helpful instrument for evaluating their outcome.

From the standpoint of waste management the Flemish government uses the Lansink ranking that is the representation of the waste management hierarchy. According to this ranking prevention should be selected above recycling, incineration with energy recuperation, incineration and landfill.

In the reviewed Household Waste Implementation Plan (Braekevelt et al., 2008), waste prevention is defined as the qualitative and quantitative reduction of waste materials and their harmfulness by reduction at the source. Composting at home also belongs to waste
prevention since it encompasses organic-biological waste that is recycled at the source and thus not offered to the waste collection system.

3. Conceptual model of integrated household waste management

To study the dynamic effects of household waste prevention, collection, re-use and recycling, the Flemish closed-loop solid municipal waste management system is first modelled. Based on the revised Household Waste Implementation Plan (Braekevelt et al., 2008) Implementation Plan of Organic-biological Waste (Interne OVAM werkgroep, 2000), the overview report of biomass availability and use 2006-2007 (Andries and Loncke, 2008), the study of renewable energy in Flanders (Devriendt et al., 2005) and various meetings with a team of OVAM experts on waste management, the representation of the waste collection and valorisation chain was obtained as represented in Figure 1 in which numbers are used to refer to the flows discussed below. The numbers in the discussion below that refer to the numbers of Figure 1 are indicated between brackets. For more detailed information, the reader is referred to the revised Household Waste Implementation Plan (Braekevelt et al., 2008).

Figure 1: Domestic waste collection and disposal in Flanders (conceptual model)
Basically, the production of household waste comes from domestic consumption of solid material such as newspapers, packaging material, etc. [6] resulting in the dry fraction of domestic waste and the collection of green [7] and food and kitchen waste (in Dutch: GFT afval) [8]. The dry fraction of domestic waste is composed of primary raw materials [1] and secondary –recycled- raw materials [2] together with a fraction of re-used goods [12] taken from the selectively collected waste [12].

A very marginal part of domestic waste is disposed of in an uncontrolled way [5]. Domestic waste is collected selectively [11] or non-selectively [14]. The dry fraction of selective collected waste is mainly disassembled and recycled [13] so that it can be reused as secondary raw material in the materials forward supply chain loop. The green and bio waste are mainly composted [13]. Compost is mainly used as fertilizer and is therefore also considered as secondary raw material.

Non-selectively collected domestic waste is nowadays mainly incinerated together with the comparable industrial waste (IW) according to the best available technology [18]. This means that energy is recuperated as much as possible [23] and in some installations a pre-treatment [17] takes place where the recyclable dry fractions are sorted out first. Since 1/1/2006, household waste landfill is prohibited unless no other disposal methods are available. Actually the remainders of the incineration of waste can only be used for 50% as secondary raw material in the construction of roads [19]. The remaining fraction has to be landfilled [21].

Renewable energy out of waste, also called waste-to-energy, is produced mainly by the incineration of landfill gas [22] and solid non-selectively collected waste [23]. Also fermentation of organically biological waste produces a minor portion of gas [20]. Together with other sources of renewable energy [24] an increasing portion of renewable energy is produced [25] to support the total energy demand [26] of Flanders.

4. Historical data analysis and mathematical formulation

Two main parts can be distinguished to be modelled: (i) Household waste generation, prevention and collection and (ii) Household waste handling (re-use, composting, recycling, disposal) consisting of material waste handling and waste-to-energy flows.

4.1. Conceptual model for household waste collection

The total household waste collection per year, \( THWC(t) \), can be split up into two main components: selectively collected household waste \( THWC_s(t) \) and non-selectively collected household waste \( THWC_{ns}(t) \).
\[ THWC(t) = THWC_s(t) + THWC_{ns}(t)[10^3\text{kg} \cdot \text{year}^{-1}] \]  

(1)

The selectively collected household waste can be decomposed in two subgroups: (i) an organic-biological fraction \( OBFS(t) \), consisting of vegetables, fruit and yard waste called bio waste (in Dutch: GFT afval) and green waste and (ii) a non-organically dry fraction \( DF_S(t) \) of paper and cardboard, glass and some other smaller fractions of selective collected waste. Since paper and cardboard are collected for recycling purposes, the organic component therein contained is not taken into account in \( OBFS(t) \). Selectively collected waste is denoted with the subscript “s”.

\[ THWC_s(t) = DF_s(t) + OBFS(t)[10^3\text{kg} \cdot \text{year}^{-1}] \]  

(2)

To compare the waste management performance of the European member states and regions with each other, domestic waste is expressed per capita denoted with the subscript “c”. Therefore equation (2) is rewritten as

\[ THWC_s(t) = THWC_{s,c} \cdot POP(t) = [DF_{s,c}(t) + OBFS_{s,c}(t)] \cdot POP(t) \]  

(3)

Following the OVAM reviewed Household Waste Implementation Plan 2008 (Braekevelt et al., 2008) the generation of household waste will be modelled as a function of GDP growth, population growth, and selective collection behaviour reflected by the switch from non-selective to selective waste collection. Prevention should be also taken into account but to the best of our knowledge yearly-collected data does not exist. The available 1991-2006 data is represented in Figure 2 (Statbel, 2008).
Clearly the dependent variables are not constant over time and as such their behaviour needs to be modelled to allow for dynamic simulation. As detailed below, the best fit for the population growth is an exponential function, for the GDP growth a linear function is more appropriate and for the reuse and recycling behaviour a logistic growth function is selected. The latter variable can be more accurately described by a cubic function. However, since it is our goal to model selective collection behaviour and prevention separately the logistic growth function is preferred. The authors assume that the decline in selective collection behaviour, as derived directly from the total selectively collected household waste during the last 3 years (2003-2006) is due to increased prevention such as e.g. the increase in home composting, the reduction of non renewable packaging and the increase of reused goods due to the considerable efforts made during that period (Braekevelt et al., 2008). Prevention will be separately modelled given its crucial role in sustainable waste management policy. The $R^2$ statistic measures the strength of association between the observed and model-predicted values of the dependent variable, time. The curves are fitted based on 16 data points (1991-2006). For scaling purposes GDP and Population values for 1991 are expressed as an index (basis 1991=100). Equations (4), (5), (6), (7) and (8) were all generated by SPSS with a significance level of $p= 0.000$.

\[
POP(t) = 5,781,726 \cdot e^{0.003t}[\text{capita}]; R^2 = 0.960
\]  \hspace{1cm} (4)

\[
POPI(t) = 99.769 \cdot e^{0.003t}[\text{capita} \cdot \text{year}^{-1}]; R^2 = 0.981
\]  \hspace{1cm} (5)

\[
GDPI(t) = 95.406 + 2.474(t)[\text{Euro} \cdot \text{year}^{-1}]; R^2 = 0.988
\]  \hspace{1cm} (6)

The selective collection behaviour $SCBEH(t)$ expresses the percentage of the household waste that is collected selectively and is represented by a figure in the interval $[0, 75]$. This figure is derived from the Statbel data of the selectively collected waste after extracting the GDP and Population effect from the data. As reference, the value in 2005, i.e. $t = 15$ is chosen as $SCBEH(15) = 70$. This corresponds with the OVAM statement that 70% of the intended selective waste fractions were effectively selectively collected in 2005. The maximum of selectively collected waste until 2015 is estimated as 75%. $SCBET(t)$ can be described by the cubic function (7) or the logistic growth function (8). It is the latter that will be used from now on in this article.

\[
SCBEH(t) = 10.462 + 3.803t + 0.601t^2 - 0.039t^3[\%]; R^2 = 0.984
\]  \hspace{1cm} (7)

\[
SCBEH(t) = \frac{1}{\frac{1}{75} + 0.048 \cdot 0.729^t}[\%]; R^2 = 0.791
\]  \hspace{1cm} (8)
4.2. Conceptual model for selectively collected household waste

The selectively collected dry fraction $DF_s(t)$ and the selectively collected organic biological fraction $OBF_s(t)$ are examined on their relationship with the independent variables $GDPI(t)$ and $SCBEH(t)$ and $POPI(t)$ using the statistical technique of multiple linear regression analysis. In the equations that are derived using this technique, the independent variables that contribute to the regression with a significance level of less than 95% are withdrawn. Each equation (9, 10) contains a set of figures that are noted in parentheses. The first set are the estimated standard errors, SE, of the regression coefficients, the second set are the estimated t values computed under the null hypothesis that the true population value of each regression coefficient individually is zero. The figures in the third set of parameters are the estimated p values. Values of $p \leq 0.05$ contribute to the regression with a significance level of at least 95%, which means that they are considered to be relevant in explaining the relationship with the dependent variable in the equation. Apart from the three sets of figures, some other single figures describing the quality of the regression are presented: $R^2_{adj}$ is the adjusted multiple coefficient of determination that expresses the goodness of fit of the regression equation. The closer $R^2_{adj}$ is to 1, the better the fit is. The adjusted R-squared, $R^2_{adj}$, compares the sample size to the number of terms in the regression model. In doing so, it offers an appropriate measure of fit for regression models that have few samples per term such as the ones presented in the next two sections. In time series, autocorrelation may occur meaning that members of observations ordered in time are correlated. Autocorrelation should be detected and corrected. The Durbin-Watson d statistic is a test for detecting serial correlation (Gujarati 1995). Finally the regression coefficients are examined on the presence of multicollinearity, meaning that the independent variables are to some extent inter-correlated. The extent of inter-correlation is expressed in the VIF factor. Both auto-regression and multicollinearity have a negative influence on the regression accuracy. For more details, the reader is referred to Gujarati (1995). In the upcoming statistical derived equations for $DF_s(t)$, $OBF_s(t)$ and $THWC(t)$ a double logarithmic specification will be used so that the regression parameters show the elasticity of the dependent variables on the independent variable. This means that the slope coefficients of $\ln GDPI(t)$ and $\ln SCBEH(t)$ are a measure of the percentage change in $DF_s(t)$ for a percentage change in $GDPI(t)$ or $SCBEH(t)$.

\[
\ln DF_s(t) = 4.513 + 1.207 \cdot \ln GDPI(t) + 0.9 \ln SCBEH(t)[10^3 \text{kg} \cdot \text{year}^{-1}]
\]

<table>
<thead>
<tr>
<th>SE</th>
<th>(0.775)</th>
<th>(0.191)</th>
<th>(0.039)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>(5.821)</td>
<td>(6.331)</td>
<td>(23.300)</td>
</tr>
<tr>
<td>p</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
</tr>
</tbody>
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$R^2_{adj} = 0.996; d = 1.391; VIF = 4.914$

(9)
\[ \ln OBF_s(t) = 6.494 + 0.456 \cdot \ln GDPI(t) + 1.155 \cdot \ln SCBEH(t)[10^3 \text{kg} \cdot \text{year}^{-1}] \]

<table>
<thead>
<tr>
<th>SE</th>
<th>(0.831)</th>
<th>(0.204)</th>
<th>(0.041)</th>
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<tbody>
<tr>
<td>t</td>
<td>(7.818)</td>
<td>(2.232)</td>
<td>(27.895)</td>
</tr>
<tr>
<td>p</td>
<td>(0.000)</td>
<td>(0.044)</td>
<td>(0.000)</td>
</tr>
</tbody>
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\[ R_{adj}^2 = 0.977; d = 1.470; VIF = 4.914 \] 

In both (9) and (10) a high \( R^2 \) is noticed and significant t ratios together with a moderate VIF, indicating moderate multicollinearity (as a rule of thumb, variables are said to be highly collinear if VIF > 10). First-order autocorrelation using the Durbin-Watson d statistic for \( n = 16 \) and 2 dependent variables implies that the lower and upper bounds at 0.05 level of significance are \( d_L = 0.982 \) and \( d_U = 1.539 \). For both expressions (9) and (10) \( d_L < d < d_U \) which signifies that one cannot conclude whether autocorrelation does or does not exist. Because the standardized residuals are approximately normally distributed with 

\[ \hat{u}_{DF} = \hat{u}_{ow} \sim N(0;0.931) \]

the presence of autocorrelation is rejected. Finally, there is no indication of spurious regression in (9) and (10) because the Durbin-Watson d statistic is larger than the \( R^2 \) statistic (Gujarati, 1995).

The selectively collected household waste (without the effect of prevention) can be written by filling (9) and (10) into (2) as

\[ THWC_s(t) = 91.194 \cdot GDPI(t)^{1.207} \cdot SCBEH(t)^{0.9} + 661.163 \cdot GDPI(t)^{0.456} \cdot SCBEH(t)^{1.155}[10^3 \text{kg} \cdot \text{year}^{-1}] \] 

(11)

4.3. Conceptual model for prevention

To the best of our knowledge, there is no annual historical data available on the prevention of selectively collected waste in Flanders. In the reviewed Household Waste Implementation Plan 2008 (Brackevelt et al., 2008), OVAM has set a goal of 5% re-use of the material for the dry fraction in 2010. Moreover, OVAM has decided that the prevention for the dry fraction of the household \( GPREV_DF(t) \) waste has to be in line with the autonomous growth of the population and GDP as from 2005. For the prevention of the organic biological fraction \( GPREV_OBF(t) \) OVAM decided that this only has to be in line with the population increase as from 2005.

The prevention goal function \( GPREV(t) \) as set out by OVAM will therefore be expressed from 2005 onwards as

\[ GPREV(t) = DF(t) \cdot a_1 \cdot [POPI2005(t) + GDPI2005(t)] + OBF(t) \cdot a_2 \cdot POPI2005(t) \] 

(12)
in which \( a_1, a_2 \) are scaling factors in the SD-model for simulating an increased/decreased prevention with respect to the planned prevention \( GPREV(t) \).

\[
POPI_{2005}(t) = \frac{POP(t) - POP(2005)}{POP(2005)}
\]

\[
GDPI_{2005}(t) = \frac{GDPI(t) - GDPI(2005)}{GDPI(2005)}
\]

4.4. Conceptual model for non-selectively collected household waste

The non-selectively collected household waste can be derived from (1) as

\[
THWC_{ns}(t) = THWC(t) - THWC_s(t)
\]

For the total amount of collected household waste \( THWC(t) \), only \( GDP(t) \) was statistically significant in the regression equation (16.) Both \( POPI(t) \) and \( SCBEH(t) \) were not statistically significant for a significance level of at least 95%

\[
\ln THWC(t) = 10.114 + 1.012 \ln GDP(t)[10^3 \text{kg.year}^{-1}]
\]

\[
\begin{align*}
\text{SE} & \quad (0.657) \quad (0.138) \\
\text{t} & \quad (15.391) \quad (7.318) \\
\text{p} & \quad (0.000) \quad (0.000) \\
R_{adj}^2 & = 0.778; d = 0.398 
\end{align*}
\]

With \( d = 0.398 < d_L = 0.844 \) this expression suffers from (first-order) autocorrelation. As the parameter estimates remain unbiased, and only the estimated standard errors (SEs) are biased in the presence of autocorrelation, the current formulation and estimation method is kept (for more details on handling autocorrelation, see e.g. Green (2007)).

4.5. Conceptual model for household waste management methods

Household waste management methods vary between re-use, recycling, composting and landfill as depicted in Figure 3. Selectively collected household waste can be re-used, recycled or composted. Non-selectively collected household waste is partially pre-treated (dried or separated) since 2006, incinerated or landfilled. (Statbel, 2008)
4.6. Disposal of selectively collected household waste

The dry fraction of the selectively collected household waste is either re-used or recycled. The fraction that is re-used is marginal compared to the fraction that is recycled. In 2005 3kg/capita was re-used. The goal of the Flemish government is to increase this to 5 kg/capita by 2015. Since no data is available, a linear re-use increase dating from 1991 is assumed (i.e. \( t = 0 \)) with a yearly re-use increase rate \( b = 0.2 \) [kg/year, capita]. The yearly reuse rate \( REUSE(t) \) is expressed by (17):

\[
REUSE(t) = b \cdot t \cdot Pop(t)
\]  

(17)

Apart from a small residual fraction of \( DF_s(t) \), \( RFD \), that is not suitable for recycling, the selectively collected dry fraction that is not re-used should be recycled. Based on OVAM figures, \( RFD = 0.05 \) (Braekevelt et al., 2008).

\[
REC(t) = DF_s(t) \cdot (1 - RFD) - REUSE(t)
\]  

(18)

The organic biological fraction of the selectively collected household waste is industrially composted. Compost, expressed by the yearly compost rate \( COMP(t) \), is used as fertilizer and is thus considered a secondary raw material. The yearly compost rate is composed of the yearly selectively collected organic biological fraction \( OBF_s(t) \) augmented with the amount of compost due to the extra prevention action defined since 2005 \( GPREV_OBF(t) \). The organically biological fraction rate that is exported \( OBF_e(t) \) and the amount of incinerated organic biological fraction rate \( OBF_i(t) \) are subtracted. During composting a weight loss,
WL, of about 40% takes place. A small fraction of bio waste is first fermented before composting. During the fermentation process, biogas is generated and this can be used as a source of energy.

\[
COMP(t) = (OBF_i(t) + GPREV \_ OBF(t) - OBF_i(t) - OBF_f(t))WL
\]  

(19)

4.7. Disposal of non-selectively collected household waste

Non-selectively collected household waste is mainly incinerated, \( INC(t) \), together with a remaining fraction of industrial waste \( RFIW(t) \) and the small residual fraction \( RFD \) of \( DF_s(t) \) that is not suitable for recycling. Also the potential amount of the selectively collected organic biological fraction that is incinerated \( OBF_i(t) \) is added although this is yet principally not allowed by VLAREA art. 5.4.2. The amount of waste that can be incinerated is limited by the incineration capacity \( INCC(t) \).

\[
INC(t) = \min(THWC_{ns}(t) + RFIW(t) + DF_s(t) \cdot RFD + OBF_i(t), INCC(t))
\]  

(20)

Since 2006, landfill has been principally prohibited for the disposal of domestic waste unless no other option is available. The amount of waste that is still landfilled \( LF(t) \), is the amount of the non-selectively collected household waste that cannot be incinerated in addition to the remains of waste incineration. These remains constitute about 10% of the incinerated waste of which 50% can be reused as secondary raw material for construction. The remaining 50% has to be landfilled. For non-selectively collected industrial waste that can be incinerated landfill will be prohibited at the latest by 2015 (Braekevelt et al., 2008).

\[
LF(t) = INC(t) \cdot 0.5 \cdot RF + \max(THWC_{ns}(t) - INC(t), 0)
\]  

(21)

According to the reviewed OVAM Household Waste Implementation plan of 2008

\[
RF = 0.1 \cdot INC(t)
\]  

(22)

4.8. Conceptual model for waste-to-energy

This subsection will focus on renewable energy that can be generated from the collective disposal of domestic waste in Flanders. Since there are also many public initiatives to generate electricity and heat from waste, this presents a partial overview. For the model presented, the reasonable assumption is made, based on the actual practice in Flanders, that all the energy is transformed into electricity. It should however be noted that biogas and bio waste is energetically a better fit for heat production but due to the higher subsidies for green electricity this is actually not the common practice in Flanders (Devriendt et al., 2005)
The production of electric power from domestic waste $PEW(t)$ comes from the production of electric power from the incineration of household waste $PEW_i(t)$ and the production of electric power from biogas $PEW_b(t)$ generated from the landfills and the fermentation of the organic biological fraction.

$$PEW(t) = PEW_i(t) + PEW_b(t)[MWhe \cdot year^{-1}]$$

(23)

The electricity production from incineration $PEW_i(t)$ depends on the amount of waste that is incinerated $INC(t)$, its energy content $ECWI(t)$ and conversion ratio of $ECWI(t)$ into the produced electrical power $CRI$. Although both can vary over time, $ECWI(t)$ is considered to be constant in time. For more information, the reader is referred to the reviewed OVAM Household Waste Implementation Plan of 2008(Braekevelt et al., 2008).

$$PEW_i(t) = INC(t) \cdot ECWI(t) \cdot CRI[MWhe \cdot year^{-1}]$$

(24)

$$ECWI(t) = 10[GJ \cdot 10^{-3} kg]$$

(25)

$$CRI = 0.026[MWhe \cdot GJ^{-1}]$$

(26)

Electric power produced by the incineration of biogas is generated from the collection of landfill gas and from the fermentation of the selectively collected organic biological waste. The electricity production that is derived from the fermentation $PEW_f(t)$ is only a rough estimation based on data in the reviewed OVAM Household Implementation Plan of 2008. The yearly organic biological fraction rate used for fermentation $OBF_f(t)$ is rather small. In 2004 9,000 MWh was produced by means of fermentation out of 51,000 ton bio waste.

$$PEW_f(t) = OBF_f(t) \cdot ECF [MWhe \cdot year^{-1}]$$

(27)

$$ECF = 0.176[MWhe \cdot 10^{-3} kg]$$

(28)

Biogas that is collected on landfills is related to the amount of new landfilled waste $LF(t)$, the degree of capture and the degradation effect of the production of biogas coming from previously landfilled material. For the purpose of this article only the new landfilled waste is taken into account. The energy content per ton landfilled waste $ECL(t)$ is assumed to be constant. In reality this content decreases in time but also increases by better capture. Both actions take actually place. Further investigation can give a more precise expression.

$$PEW_l(t) = LF(t) \cdot ECL(t)[MWhe \cdot year^{-1}]$$

(29)

$$ECL(t) = 0.10[MWhe \cdot 10^{-3} kg]$$

(30)

The total rough estimate of electric power production per year derived from biogas from bio-organic household waste is
In the previous section the mathematical relationships are derived that underlie the dynamic simulation tool that will be developed in this section. After validation and calibration, this simulation tool is used to evaluate the actual waste management policy in Flanders and to investigate the sensitivity of some major waste management issues. As a dynamic simulation tool, the System Dynamics (SD) approach is used. SD is a method to enhance learning in complex systems. It is increasingly being used in companies and public policy settings to design more successful policies (Sterman, 2000). In SD a model can be described by means of stock and flow diagrams underlying the physical structure of the system that is investigated. Stocks include inventories of e.g. product, population and financial accounts. Flows are the rates of increase or decrease in stocks, such as e.g. production and shipments, births and deaths, investment and depreciation. Stocks characterize the state of the system and generate the information upon which decisions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in the system (Sterman, 2000). The simulation program was developed using Vensim DSS32 v5.4a.

5.1. Forward and reverse material supply chain

The European waste management strategy is based on the fundamental principle that every country or region is responsible for disposing the waste it has produced in its own country/region. As such, the economy of Flanders can be modelled as a virtual closed-loop system with regard to waste management.

In the SD model that is presented, it is assumed that all the household consumed products produced in one year lead to household waste in the same year. According to the household waste figures of 2006 (Statbel 2009), the main fractions in terms of weight are: 39% organic kitchen and garden waste, 15% plastics, 11% paper and cardboard, 10% glass and metal. Together they cover 75% of the total collected waste. Organic kitchen and garden waste have by nature a short life and the waste derived from plastics, paper, cardboard, glass and metal is mostly waste which has also a short life such as packaging waste and newspapers (Fost Plus 2007). Since these amounts do not vary much over the years (see Statbel 2009), the 2006 decomposition of waste in terms of life cycle is also valid for the other years and thus renders our assumption acceptable. Household waste also encompasses products with a longer life such as e.g. white goods, but their volume is negligible compared to the other waste streams and hence does not influence significantly our assumption. Therefore the demand rate for household goods to the produced household waste in the same year is equalled. Products that are reused are not demanded. This is expressed in equation (32).

\[ \text{Demand rate} = THWC(t) - \text{REUSE}(t) \]  

(32)

\[ PEW_h(t) = PEW_j(t) + PEW_l(t)[MWhe \cdot year^{-1}] \]  

(31)
All products that are demanded by the customers are produced out of primary or secondary raw materials. It is assumed that the demand of household goods can be fulfilled by the production in the same year. Also sufficient material supply is assumed so that no time delays have to be taken into account. This is expressed in (33) and (34).

The total production of goods per year is made out of primary non-renewable material (PRM supply rate) and secondary renewable material (SRM supply rate). Primary raw material is used when no secondary raw material is available.

\[
\text{PRM supply rate} = \text{demand rate} - \text{SRM supply rate} \quad (33)
\]

\[
\text{SRM supply rate} = \text{Min(demand rate, SRM input rate)} \quad (34)
\]

The other mathematical equations previously derived in this article are put into the System Dynamics model as depicted in Figure 4. Stocks are symbolized by rectangles, flow variables are symbolized by valves, and model variables by their name without a symbol added. Model variables that are defined in another view of the SD model, the shadow variables, are printed between “< >”. Stocks outside the model boundary that are used as input (source) or output (sink) and are represented by a cloud. The variables are related by causal links, denoted by arrows. Each causal link is assigned a polarity, either positive (+) or negative (-) to indicate how the dependent variable changes when the independent variable changes.

In the stocks and flows diagram of the SD-model depicted in Figures 4 and 5, the forward supply chain (equations 32,33,34), the yearly compost production \( COMP(t) \) (equation 19), the yearly amount of incinerated household waste \( INC(t) \) (equation 20), the yearly amount of landfilled household waste \( LF(t) \) (equation 21) and yearly power production \( PEW(t) \) (equation 23) are described as auxiliary variables since we assume no time delays between the production – consumption – waste management options for the household products under study in one year.

The Selective Collection Behaviour logistic growth function \( SCBEH(t) \) (equation 8) is modelled as a S-shaped Growth behaviour (see Figure 5). The model constant fractional \( SCBEH \) net increase rate was determined using Vensim for the logistic growth function \( SCBEH(t) \) to the data.
Figure 4: Forward and reverse material supply chain SD model in Flanders
5.2. Waste disposal methods and waste-to-energy

![Diagram of waste disposal methods and waste-to-energy SD model Flanders](image)

Figure 5: Household waste landfill, incineration and waste-to-energy SD model Flanders

Also for waste disposal and waste-to-energy the equations previously derived in this article are put in the System Dynamics model as depicted in Figure 5. To increase the potential of the simulation model as a decision support tool the possibility of OBF incineration, $OBF_i(t)$, and OBF export, $OBF_e(t)$, is added for the selectively collected organically biological household waste as depicted in Figure 4.

6. Simulation results

6.1. Validation of the model

Since the smallest time constant in the model is 1 year, the time stamp used in the SD simulation is 1/4 year. According to Sterman (2000) one should use a time stamp between $1/4$ and $1/10$ of the smallest time constant in the model. The model was run at $1/8$ and $1/4$ with no substantial changes. Furthermore the Euler integration method was preferred to the Runge-Kutta method because of its greater accuracy when a discontinuous element is included such as the step function for the prevention goal function of waste, $PREV(t)$, in the model.
The simulation period is 25 years starting at time $t = 0$ in 1991. The simulation results of this model end in 2016, which is comparable to the end date 2015 of the Household Waste Implementation Plan. Since all the major regulatory measures foreseen in this plan are covered in this model and since the period before 2005 is to be considered as frozen with respect to regulatory measures, the authors assume that the constant variables in the model will not become too dynamic.

The model was further checked on structural validity and extreme conditions.

A quantitative check of how the simulated and the actual data fit can be done by using the Theil inequality statistics (Sterman 2000). This provides an easily interpreted breakdown of the sources of error by dividing the Mean Square Error (MSE) into three components: bias (UM), unequal variation (US) and unequal co-variation (UC). The sum of these three components always equals 1. The model fit of the equations (9), (10), (11) and (16) with the real life data was assessed (see Table 1).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Expression</th>
<th>N</th>
<th>$R^2$</th>
<th>MAPE</th>
<th>Bias</th>
<th>Unequal variation</th>
<th>Unequal co-variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DF_s(t)$</td>
<td>(9)</td>
<td>16</td>
<td>0.987</td>
<td>0.078</td>
<td>0.583</td>
<td>0.004</td>
<td>0.413</td>
</tr>
<tr>
<td>$OBF_s(t)$</td>
<td>(10)</td>
<td>16</td>
<td>0.957</td>
<td>0.123</td>
<td>0.395</td>
<td>0.008</td>
<td>0.597</td>
</tr>
<tr>
<td>$THWC_s(t)$</td>
<td>(11)</td>
<td>16</td>
<td>0.981</td>
<td>0.088</td>
<td>0.520</td>
<td>0.008</td>
<td>0.472</td>
</tr>
<tr>
<td>$THWC(t)$</td>
<td>(16)</td>
<td>16</td>
<td>0.823</td>
<td>0.041</td>
<td>0.001</td>
<td>0.041</td>
<td>0.958</td>
</tr>
</tbody>
</table>

Table 1: Theil inequality statistics

Theil inequality statistics indicate a low unequal variation (US) for all the equations which signifies the absence of a systematic error in the trend between the model and the real life data. The equation (9) shows a rather dominant bias error due to the fact that the modelled data values for $DF_s(t)$ are almost always higher than the real-life data values. This systematic error is corrected by applying an offset of -61,289 kg for the modelled $DF_s(t)$ in the equation (9) in the SD model. The offset used is equal to the difference of the data mean and model mean for $DF_s(t)$. Consequently also equation (11) will have the offset correction since it is the sum of $DF_s(t)$ and $OBF_s(t)$. After the application of the offset correction the majority of the error for all equations is concentrated in the unequal co-variation (UC) but this has to be considered as an unsystematic error since cyclic behaviour is not of importance in the equations under study (Sterman, 2000). Table 1 also shows the point-by-point correspondence of the model measured by the Mean Absolute Percent Error (MAPE) and the coefficient of determination $R^2$. $R^2$ is in all cases near to 1 indicating that the model replicates well the real-life data. For $OBF_s(t)$ the MAPE is rather high indicating that the model does
not match very well the real-life data on all points. This difference can be explained by the seasonal differences in the yearly collection of $OBF_s(t)$. Since it does not influence substantially the MAPE of $THWC_s(t)$, no corrective measures have been taken. As an example, the comparison of selectively collected household waste per capita generated by the System Dynamics model and the original Statbel data is reported (Figure 6).

![Figure 6: Selectively collected household waste per capita (simulated versus historical data)](image)

6.2. Evaluation of Flanders’ waste management policy

In Flanders, excellent results have been achieved in selective household waste collection. In the future, the emphasis will be on increased waste prevention. If non-renewable energy prices continue to increase, waste-to-energy valorisation will also gain importance.

The SD model can be used to evaluate the Flemish household waste policy described in the introduction. First targets 2 and 3 of the reviewed Household Waste Implementation Plan (Braekevelt et al., 2008) will be examined. Target 2 aims at keeping the total household waste per capita below the maximum of 560 kg/capita. This target has to be reached by using all kinds of prevention initiatives to neutralize the growth of the household waste caused by GDP growth. To simulate the sensitivity of the amount of waste to be prevented in order to keep the total amount of domestic waste at a level of maximum 560 kg/capita for the period 2005 and later, the $a$-values will be used in equation (12). The targets set by the Flemish government are first simulated, i.e. $a_1=0$, $a_2=1$ (base run) in such a way that the amount of prevented domestic waste for the dry fraction and organic biological fraction is equal to their autonomous growth since 2005. Clearly this will result in achieving the target as depicted in Figure 7. However the sensitivity on the total domestic waste collection for a
lower or higher level of prevention than the autonomous growth of the dry faction and organic biological fraction of domestic waste is very high. A lower level of prevention of the dry fraction is represented by $0 < a_1 < 1$ and $0 < a_2 < 1$ for the organic biological fraction. A higher level of prevention is represented by $a_1 > 1$ and/or $a_2 > 1$. When $a_1=a_2=0.5$ target 2 is not reachable. In the opposite case when $a_1=a_2=2$, target 2 can be easily reached.

Figure 7: Simulation of the sensitivity of prevention on the total collected household waste per capita in Flanders

By analysing the selectively collected household waste per capita from the Statbel figures in , an indication of an increased prevention starting in 2003 ($t = 12$) is noted whereas it was planned to start from 2005 ($t=15$) onwards in the reviewed Household Waste Implementation Plan (Brackevelt et al., 2008).
It is worth noting here that a logistic growth function was preferred for the selective waste collection behaviour over the cubic function to separately model the effect of prevention on the selective domestic waste collection behaviour, represented by the logistic growth function (8) and the effect of prevention represented by (12).

The system dynamic model confirms that under the assumptions of the Flemish government, simulated at $a_1=a_2=1$, target 3 of the Flemish waste management policy can be reached. Target 3 states that the non-selectively collected waste may not exceed the level of 150 kg/capita starting from 2005. The simulation results of the influence of increased or decreased prevention, with respect to the targets of the Flemish household waste management policy, on the total amount of non selectively collected household waste are depicted in Figure 9.
Figure 9: Effect of prevention on the total non-selectively collected household waste in Flanders

6.3. Energy- To-Waste

This model can also be used to evaluate the effect of using organic biological waste for energy recovery instead of for compost production. Figure 10 shows the effect if 100,000 ton of green waste were to be incinerated instead of composted. This would lead to an increase of renewable energy but to a decrease of compost. Clearly this decision would not affect the Flemish government’s targets for household waste collection. It would only affect the increased use of non-renewable primary material for fertilizing if the amount of compost were no longer sufficient due to this decision.
7. Conclusions

In this article the dynamic effects of household waste collection and disposal in Flanders were analysed by means of a system dynamics model. After validation and calibration, this model proved to be reliable and capable of supporting integrated waste management policy issues with respect to both material and energy recuperation.

The model’s effectiveness in supporting waste policy management was illustrated by looking into the effects of prevention initiatives in Flanders. Other waste policy issues can be evaluated along the same lines. Given its generic nature and limited data requirements, the simulation model can also be used by other EC countries and regions, all of which rely on the same EC directives, to develop a sustainable approach to domestic household waste. In doing so, they should take their own data and review how the EC directives are implemented respectively in domestic legislation.

To extend the model’s capabilities in supporting integrated waste management, further research can be aimed at including waste prevention, CO$_2$ production or by further exploring the trade-off between waste-to-energy and recycling waste. Introducing additional relationships for the most important waste parameters can further enrich the model. For the selective collection behaviour it would be e.g. interesting to introduce the effect of the tax levied. Also more distinction could be made between the life cycles of the main household waste stream so that the effect of increasing these life cycles on the amount of prevented waste can be better examined. Finally, embedding delays between the production –
consumption - waste stages for the main household waste product groups could add to the understanding of the dynamic effects of the entire supply chain for household products.

Acknowledgments

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Appendix A. Used Symbols and abbreviations

Symbols

a₁: sensitivity scaling factor for the prevention goal of the dry fraction
a₂: sensitivity scaling factor for the prevention goal of the organic biological fraction
b: yearly re-use increase rate
COMP(t): industrially composted household waste in period t
CRI: conversion ratio of ECWI(t) into electrical power
DF(t): Dry Fraction of household waste in period t
ECF: energy content of fermentation gas out of one ton organic biological waste
ECL: energy content per ton landfilled waste
ECWI(t): Energy Content of Waste that is Incinerated
GDP(t): Gross Domestic Product in period t
GDPI(t): Gross Domestic Product index compared with GDP of 1991 with index = 100
GPPI2005(t) = [GDPI(t) – GDPI(2005)]/GDPI(2005)
GPREV(t): Goal of household waste to be prevented in period t
INC(t): amount of domestic and rest fraction of industrial waste incinerated in period t
INCC(t): waste incineration capacity in period t
IW(t): Industrial Waste in period t
LF(t): amount of domestic waste that is landfilled in period t
OBF(t): Organic Biological Fraction of household waste in period t
PEW(t): Electric power generated from domestic waste in period t
POP(t): Number of inhabitants in period t
POPI(t): Population index for period t referred to situation 1991 with index of population = 100
POPI2005(t) = [POP(t)-POP(2005)]/POP(2005)
PRM: Primary material
REC(t): Recycled selectively collected household waste in period t
REUSE(t): Reused dry fraction of the selectively collected household waste in period t
RF: remainder fraction after the incineration of domestic and industrial waste
RFD: residual fraction of the selectively collected dry fraction [DFₛ(t)] not suited for recycling
RFIW(t): Remaining fraction of Industrial Waste in period t
SCBEH(t): Selective Collection Behaviour in period t
SRM: Secondary Raw Material
THWC(t): Total Household Waste Collection in period t
WL: weightloss factor for composting process

Subscripts used

b: biogas
c: per capita
e: exported
f: fermentation
i: incineration
l: landfill
ns: non selectively collected
s: selectively collected
Abbreviations

IWT-Vlaanderen: Instituut voor de aanmoediging van Innovatie door wetenschap en technologie in Vlaanderen [Flemish Agency for innovation through Science and Technology]
MSW : Municipal Solid Waste
OVAM : Openbare Vlaamse Afvalstoffen Maatschappij [Flemish Public Waste Agency]
VITO : Vlaamse instelling voor technologisch onderzoek [Flemish institute for technological research]
VLAREA : Vlaams Reglement inzake afvalvoorkoming en –beheer [Flemish Decree on waste prevention and waste management]
Appendix B Model parameter values and names of variables

$a_1$ = 1  Units: dimensionless

$a_2$ = 1  Units: dimensionless

actual SCBEH = max SCBEH rate - SCBEH  Units: dimensionless

annual population increase = 0.0034  Units: dimensionless/year

average annual GDP increase = 2.474  Units: dimensionless/year

$b$ = 0.0002  Units: [ton/(year*people)]/year

COMP = $WL*(sel \text{ OBF input rate}-OBF_e-OBF_i)$  Units: ton/year

CRI = 0.026  Units: MWHe/GJ

demand rate = THWC-REUSE  Units: ton/year

desired yearly export amount = 5000  Units: ton/year

desired yearly incineration of OBF amount = 0  Units: ton/year

$DF_s$ = 91.194*POWER(GDPI, 1.207 )*POWER(SCBEH*100, 0.9 )-offset  Units: ton/year

$ECF$ = 0.176  Units: MWHe/ton

$ECL$ = 0.1  Units: MWHe/ton

$ECWI$ = 10  Units: GJ/ton

fermentation capacity = 150000  Units: ton/year

FINAL TIME = 25  Units: year

fractional SCBEH net increase rate = 0.6  Units: dimensionless/year

GDP increase rate = average annual GDP increase  Units: dimensionless/year

GDPI = INTEG (GDP increase rate, 97.88)  Units: dimensionless

GDPI2005 = step(1, 15 )*(GDPI-131.49)/131.49  Units: dimensionless

GPREV = GPREV DF + GPREV OBF  Units: ton/year

GPREV DF = $DF_s*a_1*(GDPI2005+POPI2005)/SCBEH$  Units: ton/year

GPREV OBF = $OBF_s*a_2*POPI2005/SCBEH$  Units: ton/year
INC = MIN(INCC, incineration input rate) Units: ton/year

INC remainder = INC * RF * 0.5 Units: ton/year

INCC = 1.3e+006 Units: ton/year

incineration input rate = THWCns + RFIW + DFs * RFD + OBFi Units: ton/year

INITIAL TIME = 0 Units: year

"kg/ton" = 1000 Units: kg/ton

LF = MAX(incineration input rate + INC remainder - INC, 0) Units: ton/year

max SCBEH rate = 0.75 Units: dimensionless

number of people 2005 = 6.0786e+006 Units: people

OBFe = MIN(desired yearly export amount, sel OBF input rate - OBFi) Units: ton/year

OBFf = MIN(fermentation capacity, yearly fermentation amount) Units: ton/year

OBFi = MIN(desired yearly incineration of OBF amount, sel OBF input rate) Units: ton/year

OBFs = 661.16 * POWER(GDPI, 0.456) * POWER(SCBEH * 100, 1.155) Units: ton/year

offset = -61.289 Units: ton/year

PEW = PEWf + PEWl + PEWi Units: MWh/year

PEWf = ECF * OBFf Units: MWh/year

PEWi = CRI * ECWI * INC Units: MWh/year

PEWl = ECL * LF Units: MWh/year

POP = INTEG (Population increase rate, 5,79486e+006) Units: people

POPI2005 = step(1, 15) * (POP - number of people 2005) / number of people 2005 Units: dimensionless

Population increase rate = anual population increase * POP Units: people/year

PRM supply rate = demand rate - SRM supply rate Units: ton/year

Recycling = DFs * (1 - RFD) - REUSE Units: ton/year

REUSE = POP * REUSE rate Units: ton/year
reuse increase rate = \( b \) Units: \( \text{ton/(year*people)/year} \)

REUSE rate = \( \text{INTEG (reuse increase rate,0)} \) Units: \( \text{ton/(year*people)} \)

RF = 0.2 Units: dimensionless

RFD = 0.05 Units: dimensionless

RFIW = 850000 Units: ton/year

SAVEPER = TIME STEP Units: year

SCBEH = \( \text{INTEG (SCBEH net increase rate,0.16)} \) Units: dimensionless

SCBEH net increase rate = actual SCBEH \times \text{fractional SCBEH net increase rate} \times \text{SCBEH}

Units: dimensionless/year

sel OBF input rate = OBFs + GPREV OBF Units: ton/year

SRM after INC rate = INC \times RF \times 0.5 Units: ton/year

SRM input rate = COMP + Recycling + SRM after INC rate Units: ton/year

SRM supply rate = \text{MIN(demand rate, SRM input rate)} Units: ton/year

THWC = 24686*POWER(GDPI, 1.012 ) - GPREV Units: ton/year

THWCc = THWC * "kg/ton" / POP Units: kg/(year*people)

THWCns = THWCc - THWCsc Units: ton/year

THWCnsc = (THWCns / POP) * "kg/ton" Units: kg/people/year

THWCs = DFs + OBFs - GPREV * SCBEH Units: ton/year

THWCsc = (THWCs / POP) * "kg/ton" Units: kg/people/year

TIME STEP = 0.25 Units: year

Total production of domestic goods = \( \text{INTEG (+PRM supply rate + SRM supply rate - demand rate,0)} \) Units: ton

WL = 0.4 Units: dimensionless

yearly fermentation amount = 60000 Units: ton/year