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A SIMPLE MODEL TO INCLUDE HUMAN EXCRETION AND WASTEWATER TREATMENT IN LIFE CYCLE ASSESSMENT OF FOOD PRODUCTS

Authors:
Ivan Muñoz, Llorenç Milà i Canals, Roland Clift, Gabor Doka

CENTRE FOR ENVIRONMENTAL STRATEGY
University of Surrey

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Authors:

Ivan Muñoz, Centre for Environmental Strategy (CES), University of Surrey, UK

Llorenç Milà i Canals, CES, University of Surrey, UK

Roland Clift, CES, University of Surrey, UK

Gabor Doka, Doka Life Cycle Assessments, Zurich, Switzerland

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EXECUTIVE SUMMARY

This document describes a model designed in the framework of the RELU-funded project "Comparative Merits of Consuming Vegetables Produced Locally and Overseas", in order to determine the environmental burdens of the end-of-life phase of food products in Life Cycle Assessment (LCA) studies. The model includes such processes as human excretion due to food intake, auxiliary processes related to toilet use, and treatment of human excretion products present in wastewater through a sewage treatment plant.

Any kind of food, either liquid or solid, is suitable of being assessed by this model, as long as its composition is known.

The model has been built as an excel spreadsheet in which the user is requested to introduce the composition of the food product to assess, as well as some boundary conditions related to toilet use and wastewater treatment. Once this step is accomplished, the model yields a disaggregated inventory table of the whole process: human excretion, wastewater treatment, and sludge treatment considering sludge application to agricultural soil. This excel spreadsheet can be freely downloaded from www.surrey.ac.uk/CES/.

In addition to the excel spreadsheet, this model has also been introduced in the GaBi software (www.gabi-software.com) as a group of parameterised processes including the same processes mentioned above, which can be connected to the other life cycle phases of different food products. These processes are also available for download as a GaBi 4.2 Export (GBX) file at www.surrey.ac.uk/CES/. Both the excel spreadsheet and the GaBi 4.2 processes may be used for free as long as the initial source is cited.

The present document describes in detail the human excretion and wastewater treatment model. All the calculations are illustrated by means of a practical example on boiled broccoli, displayed in text boxes. The excretion part of the model illustrated with the example of boiled broccoli will be published in:

Muñoz I, Milà i Canals L, Clift R. *Consider a spherical man - A simple model to include human excretion in Life Cycle Assessment of food products*. Submitted.

Please use this reference if the model is used.

1. INTRODUCTION

The biochemical transformations undergone by food in the human body give rise to different pollutants released to air and water, which should be included within the system boundaries of a complete food Life Cycle Assessment (LCA), in a similar way as it is done when food waste is landfilled or composted. This is particularly relevant in attributional food LCA in order to identify the life cycle hot spots.

One of the goals of the RELU-funded project "Comparative Merits of Consuming Vegetables Produced Locally and Overseas" (http://www.bangor.ac.uk/relu) is to assess the environmental hotspots in the food supply chain; thus it needs to include the emissions related to food consumption and excretion. This document describes a model designed to determine the environmental burdens of the end-of-life phase of food products in LCA studies. It includes such processes as human excretion due to food intake, auxiliary processes related to toilet use, and treatment of human excretion products present in wastewater through a sewage treatment plant.

2. HUMAN EXCRETION

This part of the model can be in turn divided in two parts: the first one (sections 2.1 and 2.2) determines the overall balance of materials in the human body, as a consequence of ingestion of food with a specific composition, whereas the second part (section 2.3) attempts to determine the auxiliary materials and energy associated with toilet use. Figure 1 shows a flow diagram of the system modelled.

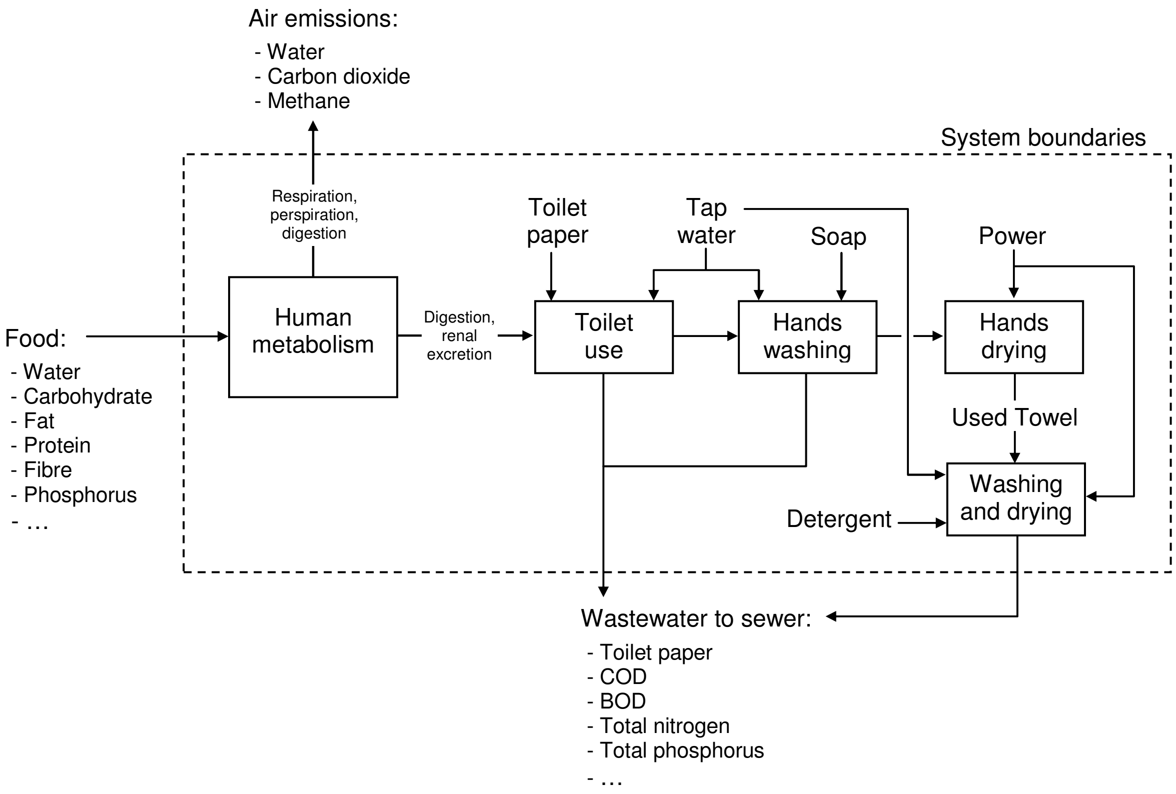


Figure 1. Modelled system.

2.1. Input to the model: food composition

In order to use the model, we need to introduce first of all the composition of the ingested food. This information is basic for human metabolism modelling, and therefore the user must provide it. Table 1 summarizes all the input parameters to be defined.

Table 1. Input data for the human excretion model, in g per 100 g edible portion.

Food constituents	Comments
Water	Water content of food.
Protein	Protein content of food.
Fat	Fat content. Total weight of lipids, including saturated and non-saturated fatty acids, cholesterol, etc.
Carbohydrate	Carbohydrate content. Includes total amount of sugars as well as starch.
Fibre	Fibre content.
Alcohol	Alcohol content, in weight (not in volume).
Organic acids	Organic acids due to fermentation processes, such as acetic acid, lactic acid, etc.
Phosphorus	Weight of elemental phosphorus.
Other inorganics	Other elements, such as Na, Cl, Mg, Ca, K, Fe, and heavy metals.

Some information on food composition can be easily found in food packaging. Nevertheless, it is recommended to check the data with a reference handbook, like *McCance and Widdowson's the composition of foods* (Food Standards Agency, 2002). It is important to introduce the composition of the food as it is ingested, since cooked or boiled food can have a very different composition as compared to raw food.

The occurrence of toxic organic compounds in food, like pesticides, veterinary drugs, etc., is not taken into account. As toxic compounds, only heavy metals are allowed to be included in the food composition. But it is important to bear in mind that the purpose of this model is to obtain a life cycle inventory; impacts on human toxicity due to exposure to these heavy metals via food are not assessed.

BOX 1. Composition of boiled broccoli.

All the calculations described in this document are illustrated by means of a practical example on boiled broccoli. The table below shows the average composition, on a fresh weight basis, of 100 g raw and boiled broccoli. It can be seen that broccoli, as many other fruits and vegetables, consists mostly of water, and only around 10% is constituted by solids. The data on raw broccoli is displayed only to show that it is important to use as input to the model the composition of food as is ingested and not as raw food, since the composition can change to a great extent: boiled broccoli has 30% less carbohydrates, 39% less proteins, and 34% less phosphorus.

Component	Broccoli, green, raw	Broccoli, boiled in unsalted water
Water (g/100g)	88.2	91.1
Main organic constituents:		
Protein (g/100g)	4.4	3.1
Fat (g/100g)	0.9	0.8
Carbohydrate (g)	1.8	1.1
Fibre (g/100g)	2.6	2.3
Inorganic constituents:		
P (g/100g)	0.087	0.057
Na (g/100g)	0.008	0.013
K (g/100g)	0.37	0.17
Cl (g/100g)	0.1	0.023

Source: Food Standards Agency, 2002.

2.2. Human metabolism modelling

2.2.1. Excretion processes

One of the basic assumptions of this model is that a 'steady state' person is considered. This means that all degradable material entering the body as food will be excreted, including proteins and fat. Therefore, no accumulation of fat or synthesis of additional proteins is considered. As a consequence, all ingested food is converted to excretion products and expelled from the body by one of the following excretion flows:

- Breath
- Urine
- Faeces
- Skin/sweat

This assumption will not particularly hold true for growing individuals, but the percentage of food retained by the human body for synthesis of tissues can be considered negligible on average. We can illustrate this with the following rough estimation: let's consider 20 years as developing period for a person, an increase in weight of 70 kg during this period, and a food basket of 11.68 kg/week/person (Pretty et al. 2005). The percentage of food locked in the human body from these figures is 0.57%, which can be neglected. In addition, only a fraction of the total population is in the development phase, which makes the percentage even lower from an overall perspective.

Figure 2 shows an overview of the fate of the initial food constituents in the human body. As it can be seen, food constituents are categorised in four groups: water, degradable organic material (the digestible fraction of food), non-degradable organic material (dietary fibre), and inorganic compounds. The main transformation route for food is the “human metabolism” process in figure 2, which affects only degradable organic material.

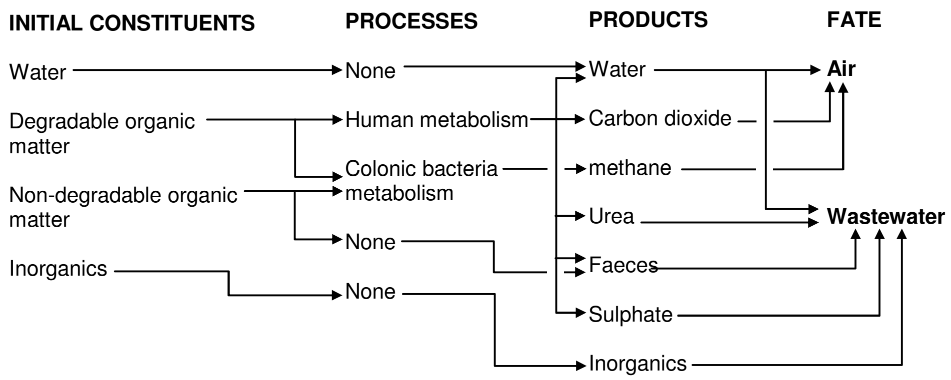


Figure 2. Fate of food constituents in the human body as considered in the model.

The first step to model human metabolism is to define a general biochemical reaction, which in turn requires, first, to know which food constituents will be subject to such reaction, and second, their chemical composition.

From the constituents in table 1, the general human metabolic reaction considered by the model takes into account as degradable materials: protein, fat, carbohydrate, alcohol, and organic acids, while fibre is basically considered as inert, as are also water and all inorganics. Table 2 summarizes the average elemental composition for all these food constituents, and how they have been estimated.

Table 2. Elemental composition of organic constituents in food.

Food constituents	Elemental composition (kg/kg)					Comments
	C	H	O	N	S	
Protein	0.47	0.07	0.29	0.15	0.02	Average C, H, N, O, and S weight of 1 mol of each of the 20 amino acids: Alanine, Arginine, Asparagine, Aspartic acid, Cysteine, Glutamic acid, Glutamine, Glycine, Histidine, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Proline, Serine, Threonine, Tryptophan, Tyrosine, Valine.
Fat	0.77	0.12	0.12	0.00	0.00	Based only on triglycerides, which constitute more than 90% of total fat intake in western diets (Boron and Boulpaep, 2003). Sum of C, H, and O weight of 1 mol of two triglycerides used as models: Triglyceride of palmitic acid, oleic acid, alpha-linoleic acid, and triglyceride of palmitic acid, palmitic acid, palmitoleic acid.
Carbohydrate	0.42	0.06	0.52	0.00	0.00	Average C, H, and O weight of 1 mol of each of the following carbohydrates:Fructose, Sucrose, Maltose, Lactose, and Starch.
Alcohol	0.52	0.13	0.35	0.00	0.00	Based on the empirical formula of ethanol, C_2H_5OH.
Organic acids	0.40	0.07	0.53	0.00	0.00	Based on the empirical formula of acetic acid (CH_3COOH) and lactic acid ($C_3H_6O_3$).
Fibre	0.44	0.06	0.49	0.00	0.00	Dietary fibre includes lignins, pectins, and cellulose (Boron and Boulpaep, 2003). The composition of fibre is based on the empirical formula of cellulose, $(C_6H_{10}O_5)_n$.

From the above composition, and taking into account the amount of each group of compounds, an empirical formula can be determined for digestible fraction of the food ingested. This empirical formula must exclude fibre, since it is considered non-digestible.

BOX 2. Calculating the empirical formula of degradable organic matter in boiled broccoli.

100 g boiled broccoli contain, in fresh weight, 3.1 g, 0.8 g, and 1.1 g of protein, fat, and carbohydrate, respectively (Food Standards Agency, 2002). Applying the weight fractions in table 2 to each of these constituents, the following weighed elemental composition for the degradable fraction of broccoli is determined:

0.50 g C/g 0.08 g H/g 0.31 g O/g 0.09 g N/g 0.01 g S/g

In order to obtain the empirical formula, we divide each element by its molar weight (12 for C, 1 for H, 16 for O, 14 for N, and 32 for S):

0.042 mol C 0.08 mol H 0.0195 mol O 0.0065 mol N 0.00045 mol S

Finally, the resulting figures are divided by the lowest figure, in this case that of sulphur, obtaining the following empirical formula for degradable organic matter in boiled broccoli:

$C_{93}H_{171}O_{43}N_{15}S$

Remember that this formula refers not to the whole food, but only to 5% in weight of it (5g of fat plus protein plus carbohydrate per 100 g). The remainder is some fibre (2.3 g) and mostly water (91.1 g).

In order to quantify the excretion products obtained as a result of human metabolism, the following overall transformation is considered:

$$\text{Degradable material + oxygen} \longrightarrow \text{carbon dioxide + water + urea + sulphate + faeces} \quad [1]$$

Which is stoichiometrically expressed as follows:

$$C_aH_bO_cN_dS_e + A\,O_2 \longrightarrow B\,CO_2 + C\,H_2O + D\,CH_4ON_2 + E\,H_2SO_4 + F\,C_2H_4O \quad [2]$$

This equation implies that organic degradable matter is converted, by cell respiration, to carbon dioxide and water, while some carbon is lost in urea, and faeces. It is assumed, to simplify the calculations, that all nitrogen from protein degradation ends up in urea, thus faeces only contain carbon, hydrogen, and oxygen, in a molar proportion similar to that of activated sludge in wastewater treatment plants (Chu and Chen, 2004). All sulphur ends up as sulphate, which is quantified as sulphuric acid in order to have an electrically neutral reaction. Some sulphur will actually be "excreted" via hair and nails growth, but this has been neglected from the model for the sake of simplicity.

For equation 2 to be solved, the share of carbon incorporated in each of the three possible products must be defined. This has been done by taking a look to the average balance of degradable carbon in the human body (table 3).

Table 3. Carbon balance in the human body.

Output	**g C/day**	**%**	**Comments**
Breath (CO_2)	195	86.9	Average from two sources. Source 1: alveolar volume is 350 ml, of which 5% in volume is CO_2. Breathing rate is 12/min. Pressure is 1 atm and T 310 K (Boron and Boulpaep, 2003). Source 2: considers 5.2% of CO_2 in alveolar volume, and a breathing rate of 20/min (Marieb, 1995). This results in 143 and 247 g C/person/day, respectively.
Urine (organic matter)	11	4.7	Urine production is 1.5 L/day (Boron and Boulpaep, 2003) with a dry weight of 5% (Mara, 2003), and a carbon content of 14% in dry weight (Feachem et al., 1983).
High molecular weight organic matter in faeces (from fibre)	7	3.0	Average intake of fibre in the UK is 15 g. It is assumed that it is excreted via faeces without any transformation, with a carbon content of 44% (table 2).
Low molecular weight organic matter in faeces (from digestible organic matter)	12	5.4	Faeces production is 0.15 kg/day, with a dry weight of 25% and a carbon content of 50% in dry weight (Feachem et al., 1983). This gives 19 g C, of which the contribution of fibre, 7 g, is extracted.
Total	225	100	Several flows have been neglected: carbon dioxide and methane in intestinal gas, and methane expelled via lungs. Altogether, these represent less than 0.1% of the carbon output.

The balance in table 3 allows to determine that, if we exclude the "inert" carbon contained in fibre (7 g/person/day), the losses of degradable carbon via faeces are (19 - 7) / (225 - 7) = 5.5%. It is worth noting that a similar amount is lost via urine, being around 90% the amount of carbon effectively used by cell respiration and transformed to carbon dioxide.

With this information, equation 2 can already be solved. The solution to the different parameters are as follows:

$$E = \mathrm{e} \quad [3]$$
$$D = \mathrm{d}/2 \quad [4]$$
$$F = 0.055\mathrm{a} \quad [5]$$
$$B = \mathrm{a} - D - F \quad [6]$$
$$C = (\mathrm{b} - 4D - 2E - 4F)/2 \quad [7]$$
$$A = (C + D + 4E + 2F + 2B - \mathrm{c})/2 \quad [8]$$

2.2.2. Fate of excretion products

The fate of each one of the final products obtained in equation [2] is considered as follows:

- Carbon dioxide is entirely emitted to atmosphere via lungs.

- Urea, sulphate, and faeces are expelled by the body as liquid+solid excreta: urea dissolved in urine, faeces as solid, while sulphate seems to be almost entirely excreted in urine (Florin et al., 1991).
- Water will be emitted as a liquid as well as a gas. In order to determine the share of each, a water balance in the human body has been estimated. As can be seen in table 4, 64% of the water output corresponds to the liquid phase (urine plus faeces), while the remaining 36% corresponds to the air phase (skin, sweat, breathing). In addition to the water originated by means of cell respiration, the model must also determine the fate of water originally present in food, which in many cases will be an amount much more important. The fate factors determined in table 4 also apply to that water.

The fate of inorganic compounds initially present in food, like phosphorus, sodium, etc., is wastewater, either through urine or faeces. These compounds, as shown in figure 1, are not subject to any transformation in the human body. They are partitioned in urine and faeces using the same fate factors than water (table 4), except for phosphorus, which is partitioned according to the following rules: 64% to urine, and 36% to faeces, according to Boron and Boulpaep (2003).

Table 4. Water balance in the human body.

Urine	1.50 L/day
Faeces	0.10 L/day
Skin/sweat	0.55 L/day
Exhaled air	0.35 L/day
% of water reaching sewage, faeces	4
% of water reaching sewage, urine	60
% of water to atmosphere	36

BOX 3. Calculating the degradation products of boiled broccoli.

The table below summarizes an example of application of the calculations described up to this point, using boiled broccoli as an example. Equations 3 to 8 allow to calculate the amount of oxygen and products involved in the biochemical reaction, expressed as moles, which in turn can be converted to g or kg by means of the molar weight of each molecule. It must be noted that degradable organic material only refers to the sum of protein, fat, and carbohydrate. In broccoli, these three groups amount to 50g/kg fresh weight, being the remaining weight mainly water and some fibre.

Inputs	**Formula**	**Moles**	**Molar weight (g/mol)**	**g**
Degradable organic material	$C_{93}H_{171}O_{43}N_{15}S$	1	2219	2219
Oxygen	O_2	99	32	3157
Outputs	**Formula**	**Moles**	**Molar weight (g/mol)**	**g**
Carbon dioxide emitted to atmosphere	CO_2	81	44	3560
Water emitted to atmosphere	H_2O	23	18	422
Water emitted in urine+faeces to wastewater	H_2O	42	18	750
Urea emitted in urine+faeces to wastewater	CH_4ON_2	7	60	435
Sulphate (as sulphuric acid) emitted in urine+faeces to wastewater	H_2SO_4	1	98	98
Organic material emitted in urine+faeces to wastewater	C_2H_4O	3	44	110

Non-degradable organic matter, that is, dietary fibre, is not available for digestion, and it is excreted via faeces. Nevertheless, fibre has been considered as a contributor to methane emissions, as discussed in the next section.

2.2.3. Methane emissions

In addition to cell respiration, the only additional chemical transformation considered by the model is the formation of methane by colonic bacteria. In carbon terms, the amounts may seem negligible, but from a greenhouse gas perspective they may not be. For this reason, an attempt has been made to estimate the amount of methane emitted by the human body due to the activity of anaerobic bacteria in the intestine.

Human cells have no metabolic path responsible of producing methane; therefore all methane produced is attributed to the action of intestinal bacteria. In addition, human cells are not able to take any profit of the produced methane, and thus it is entirely excreted either via intestinal gas or (surprisingly) via lungs (Bond et al., 1971). Another aspect worth mentioning is the fact that some subjects, approximately 1/3 of the population, continually produce large quantities of this gas, while others consistently excrete little or no methane at all (Levitt and Bond, 1980).

According to Bond and coworkers (1971), the average methane excretion rate of methane producers is 0.33 mL/min and 0.45 mL/min via lungs and intestine gas, respectively. If a pressure of 1 atm and a body temperature of 310 K are considered, this suggests that a methane producer emits 0.52 g C-CH_4 per day, or 0.69 g CH_4 per day. If this is corrected to take into account that only around 33% of the population are considered to be methane producers, we obtain an emission of 0.17 g C-CH_4 per person per day, or 0.23 g CH_4 per person per day. By comparing this figure to the data in table 3, we conclude that around 0.08% of the total carbon output in an average person is in the form of methane.

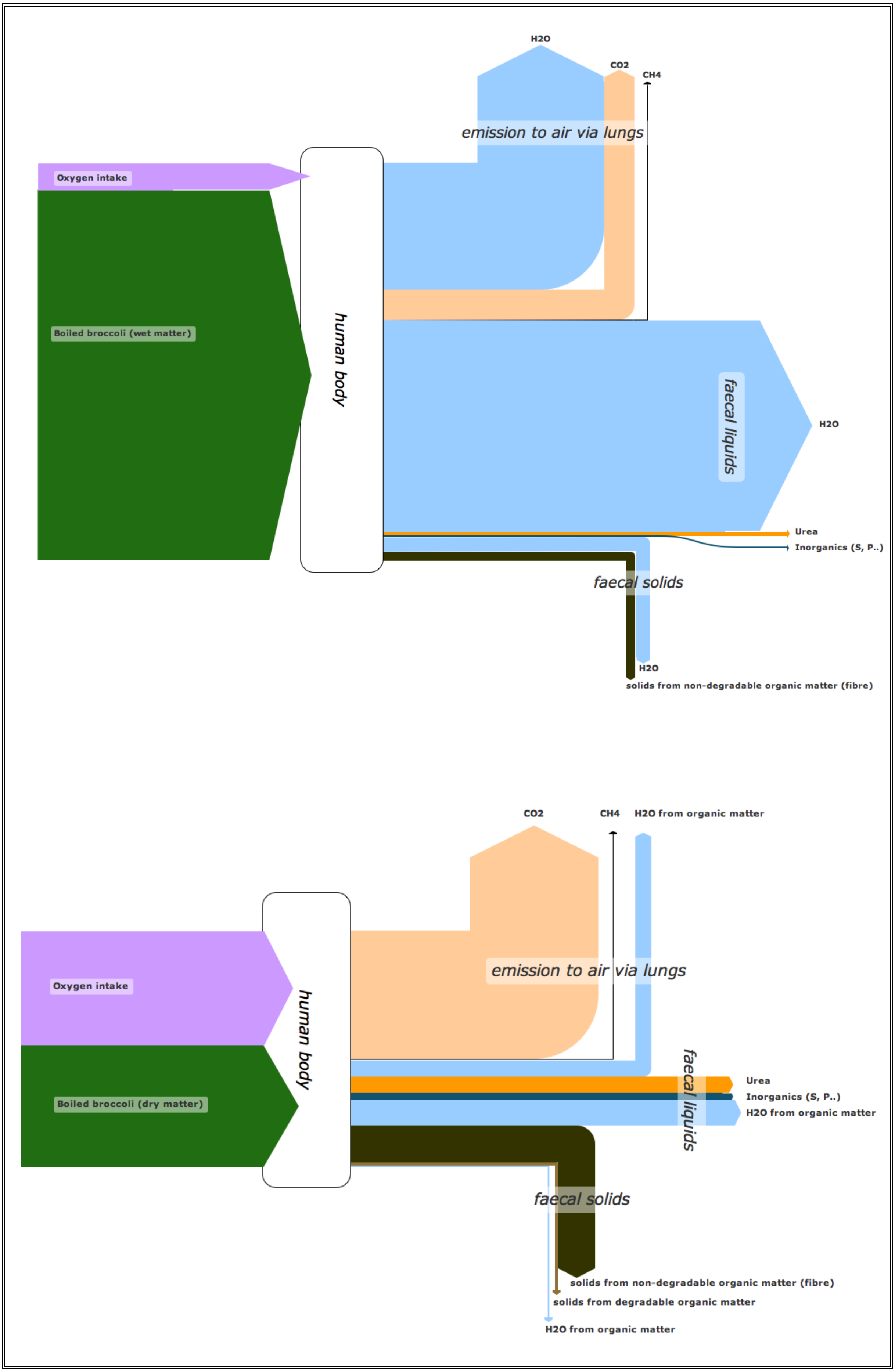
Degradable organic material contributes to methane production, but also does dietary fibre. Tomlin et al. (1991) found that a fibre-rich diet implies an increase in intestinal gas production as compared to a fibre-free diet, although Bond and co-workers (1971) did not find significant changes in methane production due to changes in non-absorbable carbohydrate intake. According to the latter, methane production is rather stable, while the production of other gases, namely hydrogen, is clearly enhanced by fibre intake. As a consequence, the model allocates methane emissions to all hydrocarbons present in the food ingested on the basis of carbon content, regardless of whether they are digestible or not.

BOX 4. Mass balance of boiled broccoli in the human body.

With the calculations described up to this point, an overall mass balance can be performed per kg ingested food for boiled broccoli. The table below summarizes this balance, in g per kg broccoli. It can be seen in the table that food does not sum 1000 g, but 987 g; the reason for this is that the composition for boiled broccoli, as displayed in Food Standards Agency (2002), is not rounded to 100%.
It is concluded with all the calculations made that 1 kg broccoli produces 640 g of solid and liquid excretion products, mostly in urine. Water present initially in food is the main contributor to all excretion flows.

INPUTS	**1058**
Food (g)	987
Oxygen (g)	71
OUTPUTS	**1058**
GAS EXCRETA	**418**
From water in food (g)	328
From degradable organic matter (g)	
Carbon dioxide	80
Water	10
Methane	0.026
From non-degradable organic matter (g)	
Methane	0.011
LIQUID EXCRETA	**577**
From water in food (g)	547
From degradable organic matter (g)	
Water	16
Urea	10
Sulphate	2.2
P in food (g)	0.36
Other inorganics in food (g)	1.9
From non-degradable organic material (g)	0
SOLID EXCRETA	**63**
From water in food (g)	36
From degradable organic matter (g)	
Water	1
Fecal matter	2
From non-degradable organic material (g)	23
P in food (g)	0.21
Other inorganics in food (g)	0.13

These results can be usefully visualised with a Sankey diagram (see below). A first diagram reveals that human digestion is mainly concerned with water, from a mass point of view. But if we take a look only at dry matter plus oxygen a more informative picture results, as displayed in the second Sankey diagram.



H2O
CO2
CH4
emission to air via lungs
Oxygen intake
Boiled broccoli (wet matter)
human body
faecal liquids
H2O
Urea
Inorganics (S, P..)
faecal solids
H2O
solids from non-degradable organic matter (fibre)
CO2
CH4
H2O from organic matter
emission to air via lungs
Oxygen intake
Boiled broccoli (dry matter)
human body
faecal liquids
Urea
Inorganics (S, P..)
H2O from organic matter
faecal solids
solids from non-degradable organic matter (fibre)
solids from degradable organic matter
H2O from organic matter

2.2.4. Pollutants in wastewater

Both solid and liquid excretion products shown in box 4 will end up in wastewater. The pollution load of the resulting wastewater is expressed in the model by the following parameters:

- Total organic carbon (TOC)
- Biological oxygen demand (BOD)
- Chemical oxygen demand (COD)
- Total nitrogen
- Total phosphorus and other inorganic constituents

TOC is determined from the carbon content in the solid and liquid excretion products, namely fibre and products of equation 1: faeces and urea. From the empirical formulas of these three products, the carbon content is 0.44, 0.55, and 0.19, respectively. Once TOC is determined, COD and BOD are estimated with the following ratios from the wastewater treatment model: TOC/BOD = 0.641, and TOC/COD = 0.479.

Nitrogen from human metabolism is considered in the model to be arising only from urea. Thus, from the amount of urea produced and its empirical formula, the nitrogen released in wastewater is calculated. The weight fraction of nitrogen in urea is 0.47.

Phosphorus and any other inorganic elements are not subject by any transformation in the model, so the initial weight defined in the food composition is the final amount released in wastewater.

2.2.5. Energy balance

From a Life Cycle Assessment (LCA) perspective, the energy balance of the above described processes is not an essential feature, since endosomatic energy, that is, metabolic energy, is not assigned an environmental impact in LCA. It is the upstream and downstream exosomatic energy related to the food chain which is assigned an impact. Nevertheless, for model completeness it seems appropriate to include this issue, specially when the mass balance is known, as this is the basic input data for the energy balance.

The model calculates the chemical energy stored in the inputs and outputs of the overall mass balance shown in box 4, based on the upper heating values of oxidable compounds (table 5). The latter include: food, methane, urea, faeces from degradable organic material, and faeces from non-degradable organic material (fibre). All the remaining materials receive an energy content of zero MJ/kg.

The energy content of all compounds is calculated on the basis of their elemental composition and the formula proposed by Michel (1938), shown below:

$$\text{Upper heating value (MJ/kg)} = -9.8324\,O + 124.265\,H + 34.016\,C + 19.079\,S + 6.276\,N \quad [9]$$

Where C, H, O, N, and S are the mass fraction of each element, in kg per kg compound.

The energy content of the food is calculated from the fraction of organic degradable material, fibre and water in fresh weight, giving a heat content of zero to the latter. The energy content in food as displayed in food labels is lower than the one obtained with these calculations, since our model includes the energy content of fibre. The latter is usually not taken into account in food nutritional data simply because our digestive system is not able to use that energy. We have decided to include it in the calculations, since this allows to get a more complete picture of the energy efficiency of the human digestive system as a function of different food types.

Table 5. Energy content considered for organic materials in human metabolism.

Materials	Upper heating value (MJ/kg)
Protein	23
Fat	40
Carbohydrate	17
Alcohol	30
Organic acids	17
Non-degradable organic material (fibre)	18
Urea	12
Faeces	26
Methane	57

Source: calculated using the method by Michel (1938).

The difference between the input energy in food and the output energy in liquid and solid excretion products is the smount actually used by the human body. In the final inventory, the latter will be assumed to be emitted to the environment as heat to the atmosphere.

BOX 5. Energy balance of boiled broccoli in the human body.

The table below shows the metabolic energy balance for boiled broccoli. As it can be seen, the energy input in food is 1.64 MJ/kg, of which 37% is lost in the different excretion products, mainly through faeces as undigested fibre. The remainder, 63%, is effectively used by cells in their metabolic processes.

Table 8. Endosomatic energy balance for broccoli.

Energy balance summary	MJ/kg food	%
Energy input	1.64	100.0
Energy output:	1.64	100.0
Energy actually used in metabolism (assumed as heat emission to air)	1.04	63.4
Energy in excretion products (lost energy)	0.60	36.6
Gas	0.002	0.1
Liquid	0.119	7.3
Solid	0.478	29.2

According to Food Standards Agency (2002), the energy content of boiled broccoli is 1 MJ/Kg, a figure much lower than that calculated above. The main reason is that in our calculations fibre is taken into account, while the Food Standards Agency does not consider it, as our digestive system is not able to use its energy. If we exclude fibre from the calculation, a value of 1.23 MJ/kg is obtained, closer to that of the Food Standards Agency.

2.3. Allocation of toilet use related processes to food

Using the toilet to evacuate liquid and solid excretion products implies, directly or indirectly, the use of several auxiliary materials and energy. The model makes an attempt to allocate all these processes to food intake, on the basis of mass of excretion products. The following basic assumptions are made:

- Every time the toilet is used, it is flushed.
- After each toilet use, hands are washed using soap and water at ambient temperature.
- At home, hands are dried by means of a towel, while at workplace, hands are dried by means of a hot air blower.
- Towel production is neglected, but towel washing and drying at home are included.
- Transport of auxiliary materials (soap, detergent, toilet paper) is not included.

In order to carry out the allocation, the first step is to estimate the amount of these processes incurred by an average person per day. For this purpose, a set of parameters have been defined and given default values representative, to a certain extent, of UK conditions (table 6). Nevertheless, the excel spreadsheet, as well as the GaBi parameterised process allow the user to modify the parameter values to make them representative of other regions or scenarios.

Table 6. Parameters and default values used for allocation of toilet use processes.

Parameter	Default value	Comments
Toilet flush volume (L)	11	Measured volume of a standard toilet tank at the University of Surrey.
Hands washing water use (L/wash)	1.5	Assumption.
Toilet uses (times/day)	5	Assumption. This includes both urination and defecation.
Toilet uses at home (%)	57%	This parameter is used to estimate the share of hand drying by means of a cotton towel. The remaining 43% is assumed to be done at work with a hot air blower The value is an assumption based on the following: 5 working days per week, 2 weekend days per week. In a working day, 3 toilet trips are made at workplace, 2 at home. On weekends, all toilet trips are made at home.
Toilet paper use (kg/day/person)	0.02	Calculated with the following data: tissue paper consumption in Western Europe in 2004 ws 4.1 million tonnes, of which 62% is toilet tissue, and 18% was consumed in UK and Ireland (European Tissue Symposium, 2005). The population of UK and Ireland in 2004 was 63.727.560 (Eurostat, 2007a).
Hands washing (liquid) soap use (g/wash)	3.3	Measured weight at University of Surrey toilet was 100 g of liquid soap dispensed per 60 pushings (1,67 g/pushing). The figure considers two dispenser pushings per wash.
Electric hot air blower power (kW)	2	Average power of a hand dryer (Handryers.net, 2005).
Time needed to dry hands (s)	30	Average drying time of a hand dryer (Handryers.net, 2005).
Towel weight (kg)	0.35	Assumed for a cotton towel.
Number of persons per household	2.4	Average for the UK (Office for National Statistics, 2007).
Frequency of towel washing (days)	7	Assumption.
Power demand of washing machine (kWh/kg towel)	0.43	Washing of the cotton towel (Group for Efficient Appliances, 1995).
Detergent use by washing machine (g/kg towel)	45	135 g detergent for a typical 3 kg load. Washing of the cotton towel (Group for Efficient Appliances, 1995).
Water use by washing machine (L/kg towel)	17.2	Washing of the cotton towel (Group for Efficient Appliances, 1995).
Power demand of towel drier (kWh/kg towel)	0.70	Drying of the cotton towel (Group for Efficient Appliances, 1995). Average of three technologies: air vented tumble driers, condenser tumble driers and condenser washer driers.

Hand washing and towel washing produce grey wastewater with a certain amount of pollutants. This contribution to wastewater has been considered in the model, assuming the composition shown in table 7.

Table 7. Composition of grey wastewater from hand washing and washing machine.

Origin of wastewater	COD	BOD	N-total	P-total
Basin wastewater (mg/L)	400	190	10	1
Laundry wastewater (mg/L)	1,270	260	10	25

Source: Approximate averages from several studies (Eriksson et al., 2002).

The figures in tables 6 and 7 allow re-calculating the parameters to express them per person per day. Next, these figures can be divided by the average daily solid and liquid excreta production by an average person, which is taken as 1.65 kg: 1.5 L urine (table 4) and 0.15 kg faeces (table 3). At this point, we are ready to allocate the toilet use processes to food intake, on the basis of solid and liquid excreta production, by using the following equation:

$$\frac{\text{Toilet-related burden}}{\text{kg food intake}} = \frac{\text{Toilet-related burden}}{\text{kg solid+liquid excreta}} \times \frac{\text{kg solid+liquid excreta}}{\text{kg food intake}} \qquad [10]$$

All these calculations are illustrated in box 6.

BOX 6. Allocating toilet-related burdens to boiled broccoli.

The table below illustrates the calculation of each toilet-related burden for boiled broccoli, as suggested in equation 10. The values in the second column are obtained by dividing the ones in the first column by 1.65 kg urine and faeces per person per day, whereas the final values in the third column are obtained by multiplying the values in the second column by 0.64 kg of solid and liquid excretion products per kg ingested broccoli (box 4).

Parameter	**Amount/ person/day**	**Amount/kg solid+liquid excreta**	**Amount/kg broccoli**
Water use for flushing (L)	55.2	33.4	21.4
Water use for hands washing (L)	7.5	4.5	2.9
Water use for washing machine (L)	0.36	0.22	0.14
Toilet paper use (g)	20	12	7.8
Hands washing (liquid) soap use (g)	16.5	10	6.5
Detergent use (g)	0.99	0.6	0.4
Power demand of air blower (kWh)	0.036	0.022	0.014
Power demand of washing machine (kWh)	0.0089	0.0054	0.0035
Power demand of towel drier (kWh)	0.014	0.0088	0.0056
COD in grey wastewater (g)	3.5	2.1	1.3
BOD in grey wastewater (g)	1.5	0.92	0.59
N-total in grey wastewater (g)	0.079	0.047	0.030
P-total in grey wastewater (g)	0.016	0.010	0.0064

2.4. Partial inventory for human excretion

The excel spreadsheet allows the possibility of obtaining an inventory table for the human excretion part of the model. It is worth noting that the main output of the system, wastewater, falls in the “output to technosphere” category. This means that the pollutants are not released to the environment, since the model assumes the household to be connected to a sewer leading to an urban wastewater treatment plant. As a consequence, in order to determine the final release of pollutants to the aquatic compartment, the wastewater treatment must be included in the system. Section 3 describes the wastewater treatment model.

BOX 7. Inventory table for boiled broccoli excretion.

The table below synthesizes the results of the calculations done so far with the example of boiled broccoli, with a life cycle inventory table structure. Such a table is the main result of the human excretion model built in the excel spreadsheet.

INPUTS	**Amount**	**Comments**
FROM NATURE		
Oxygen (kg)	0.071	Oxygen needed for catabolism of degradable constituents in food (carbohydrates, fat, and protein).
FROM TECHNOSPHERE		
Boiled broccoli (kg)	0.987	g food ingested.
Toilet paper (kg)	0.0078	Allocated on the basis of solid+liquid excreta mass.
Tap water (L)	24.4	Toilet flushing plus hand washing, plus towel washing, allocated on the basis of solid+liquid excreta mass.
Soap (kg)	0.0065	Hand washing, allocated on the basis of solid+liquid excreta mass.
Detergent (kg)	0.00036	Detergent for washing machine used for towel washing which in turn has been used to wash hands.
Power (kWh)	0.023	Electricity for hot air blower, washing machine and drier. All these processes are related to hand drying.
OUTPUTS		**Comments**
TO NATURE		
Air emissions:		
Carbon dioxide (g)	0.080	Produced by catabolism of degradable constituents in food (carbohydrates, fat, and protein).
Methane (kg)	0.000020	Produced by colonic bacteria. Degradation of all carbon-containing compounds, including fibre.
Water (kg)	0.34	Main source of water here is the initial content in food, but also water produced in cell respiration.
Heat (MJ)	1.0	Energy actually used by metabolic processes. Assumed to be emitted as heat.
TO TECHNOSPHERE		
Toilet paper (g)	0.0078	Present in wastewater.
Wastewater volume (L)	25.0	Sum of solid+liquid excreta plus tap water.
Wastewater emissions from food:		
Urea (kg)	0.0098	All nitrogen in food is assumed to be included here.
N in urea (kg)	0.0046	Fraction of urea that is actually nitrogen.
TOC (kg)	0.014	Carbon content in urea and fibre.
BOD (kg)	0.021	Related to carbon content from urea and fibre.
COD (kg)	0.028	Related to carbon content from urea and fibre.
Sulphate (kg)	0.0022	From protein metabolism.
P-phosphate (kg)	0.00057	Inorganic constituents in food.
Na (kg)	0.00013	Inorganic constituents in food.
K (kg)	0.0017	Inorganic constituents in food.
Cl (kg)	0.00023	Inorganic constituents in food.
Wastewater emissions from toilet use:		
BOD (kg)	0.00059	Related to grey wastewater.
COD (kg)	0.0013	Related to grey wastewater.
N-total (kg)	0.000030	Related to grey wastewater.
P-total (kg)	0.0000064	Related to grey wastewater.

2.5. Wastewater composition

According to European statistics, in 2005 97% of population in England and Wales is connected to sewage treatment plants, and 91% in Scotland, while there is no data for Northern Ireland (Eurostat, 2007b). As a consequence, in order to determine the final release of pollutants to the aquatic compartment, the wastewater treatment must be included in the system.

Allocation models for wastewater treatment usually require the input wastewater to be defined by the user, mainly in terms of concentration of pollutants. For this reason, besides the inventory table presented in the last section, the excretion model, in its excel spreadsheet version, provides the composition of the wastewater generated by a given food. This composition in kg/m^3, is simply obtained by dividing the mass of pollutants present in wastewater, by the total volume of wastewater generated. Toilet paper is also considered in this composition, as it is also an input to the sewage treatment plant.

BOX 8. Broccoli wastewater composition.

The table below presents the composition of the wastewater generated per kg boiled broccoli due to human excretion. The values are obtained by dividing the mass of each pollutant by a total wastewater volume of 25 L (24.36 L tap water plus 0.64 L fecal excretion products).

Toilet paper (kg/m^3)	0.31
Wastewater composition:	
N-total (kg/m^3)	185
TOC (kg/m^3)	541
BOD (kg/m^3)	868
COD (kg/m^3)	1181
Sulphate (kg/m^3)	87
P-total (kg/m^3)	2.5
Na (kg/m^3)	0.00052
K (kg/m^3)	0.0068
Cl (kg/m^3)	0.00092

3. WASTEWATER AND SLUDGE TREATMENT

The model described in this section is based in the work by Gabor Doka (Doka,2007), which is in turn based on a former publication (Zimmermann et al. 1996). The present model was devised from information contained in Doka (2003) and personal communications with Gabor Doka, Switzerland, in the years 2005 to 2007. The purpose of the adaptation is, on the one hand, to obtain a representative model for the UK conditions, and second, to create a parameterised process in the GaBi software allowing to calculate a life cycle inventory of wastewater and sludge treatment for a user-defined wastewater.

3.1. Input data

The basic input for the model is the amount of pollutants entering the plant, and the overall volume of wastewater, which in turn is an output of the excretion model described in the previous sections. We have discriminated between two different scenarios or types of treatment:

- Secondary treatment scenario: includes pre-treatment, primary treatment, and secondary treatment, namely aerobic biological degradation of carbonaceous organic matter by means of activated sludge. This scenario does not consider enhanced nutrient removal.
- Tertiary treatment scenario: includes pre-treatment, primary treatment, secondary treatment, and tertiary treatment for nutrient removal, namely nitrogen and phosphorus, the former by biological nitrification/denitrification, and the latter by chemical precipitation.

The spreadsheet allows the user to define the share of wastewater treated by each of these options. The default for the UK has been defined on the basis of total person-equivalents in normal and sensitive areas as defined by DEFRA following the European Directive on urban wastewater treatment (DEFRA, 2002). According to this source, 88.9% of person-equivalents are located in normal areas, while the remaining 11.1% are located in sensitive areas requiring tertiary treatment. The number of person-equivalents in less sensitive areas, i.e. areas requiring only primary treatment, is 0.25%, a low percentage that is simply neglected in the model.

3.2. Wastewater treatment

The wastewater treatment steps considered (figure 3) are pre-treatment (e.g. solid waste like plastic or tree leaves are removed at this stage), primary treatment consisting in a physical settling process, secondary treatment in an activated sludge bed, and tertiary treatment for nitrogen and phosphorus removal. The former is removed by nitrification-denitrification, while the latter is removed by chemical precipitation. The model includes infrastructure production and disposal, energy (electricity, fuels) and auxiliary materials consumption (chemicals) during operation. Primary, secondary and tertiary sludge is treated by anaerobic digestion and biogas is burned to obtain internal electricity and heat.

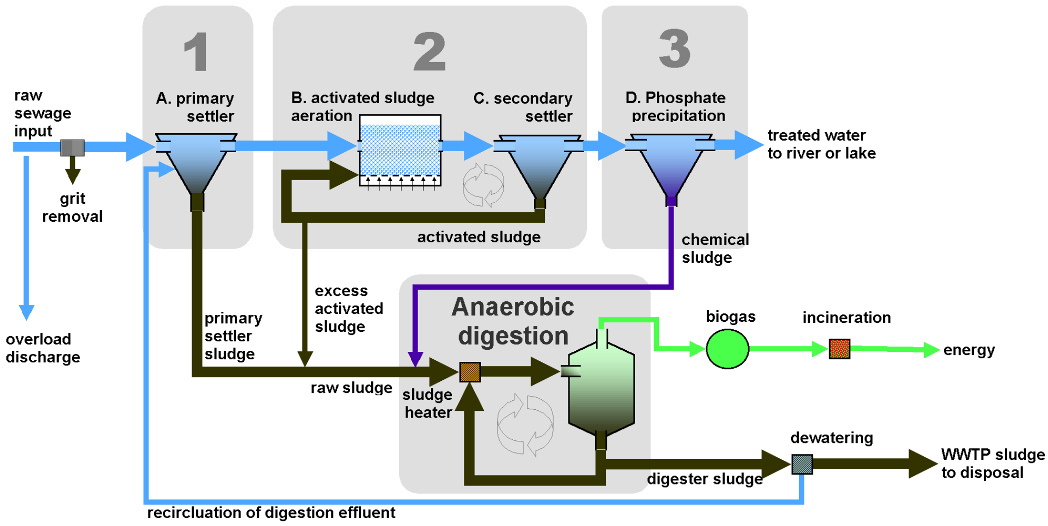


Figure 3. Wastewater treatment plant modelled.

3.2.1. Fate of pollutants in wastewater

The fate of pollutants in the input wastewater takes into account, on the one hand, overflow discharge, that is, the direct release of untreated wastewater to the aquatic environment due to hydraulic overload, for example during intense rainfall events. The wastewater actually entering the treatment is given average fate factors based on the performance of Swiss wastewater treatment plants. Table 8 shows the overall fate factors, including overload discharge and treatment.

Overload discharge assumes that 1% of the particulate contents and 2% of the dissolved contents in wastewater is discharged without treatment. The percentages in table 8 for this concept consider the share of particulate and dissolved content for each pollutant.

The fate factors for TOC, BOD, COD, and metals during treatment are taken directly from the original model, while for N, P, and S, they have been adapted taking into account the following considerations:

- Nitrogen modelling according to Doka is rather complex and is a weighed average of plants with and without tertiary treatment. For this reason, separate secondary and tertiary scenarios have been created, but much simpler. The original model differentiates 7 types of N forms in wastewater, while we consider just one, N-total, which in our wastewater is mainly dissolved as urea or maybe also as ammonium. The fate of nitrogen in the different scenarios is modelled as follows:

    - Secondary treatment scenario considers that no settling of nitrogen occurs in the primary treatment, as N is mainly dissolved and not particulate. In the activated sludge tank, nitrogen is taken up by biomass with the following ratio: 2.674 g N uptake/24.79 g N input to activated sludge tank, that is, 10.8%. Denitrification occurs to some extent, which means that first nitrification must take place. Only 3.2% of nitrogen input to secondary treatment in plants without continuous nitrification is denitrified, and 0.68% of the denitrified nitrogen is emitted as nitrous oxide, according to the original model. Denitrification is the result of converting nitrate to nitrogen gas. In our model, no other nitrate is assumed to be formed than the 3.2% that is later denitrified.

    - Tertiary treatment includes, in addition to the above processes, a denitrification zone in activated sludge bed where nitrogen is reduced (denitrified) by 32.3%. The proportions of nitrogen gas and nitrous oxide emitted to air are the same than in the secondary treatment scenario (0.68% of the denitrified N is emitted as nitrous oxide). The amount of nitrogen settled in the primary treatment is also zero, and that taken up by biomass is also 10.8%.

- Phosphorus is mainly in dissolved phosphate form. For simplicity, uptake by biomass in the secondary treatment is not considered. In the tertiary treatment scenario, phosphorus removal is carried out by means of enhanced precipitation with coagulants, namely ferric chloride, ferrous sulphate, and aluminium sulphate. The use of these metal salts as coagulants leads to an additional flow of these substances, which is taken into account in the model. Metals are assumed to be settled with sludge, while chloride and sulphate remain solved and are discharged in the final effluent.

- Sulphur is also dissolved, in sulphate form, so there is no removal at all in the primary treatment, nor is there in the secondary and tertiary treatments. Sulphur taken up by the biomass in the secondary treatment is not considered. As a consequence, 100% of input sulphate ends up in the effluent.

TOC, BOD, DOC and COD are to some extent overlapping parameters, since all of them refer mainly to organic carbonaceous organic matter (figure 4). In the model, carbon content is based on TOC, thus the carbon balance in the plant is based on this parameter. DOC, on the other hand, is not used in the model. BOD and COD are taken into account in the energy demand for aeration (see 3.2.3), and also inventoried as final emissions, since these parameters are usually included in Life Cycle Impact Assessment (LCIA), as contributors to the Eutrophication Potential. In this case it is important to bear in mind that only one of these parameters must be used in the Classification phase of LCIA, as otherwise it would mean double counting.

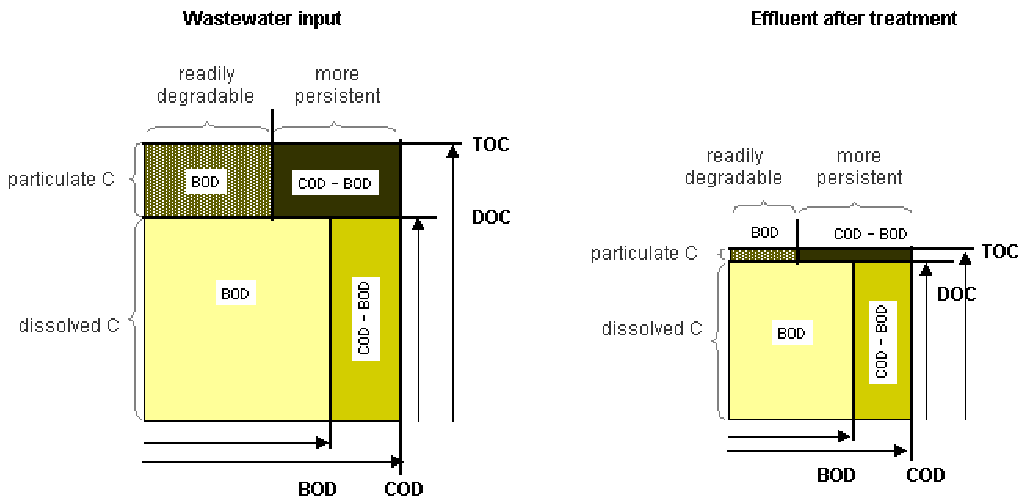


Figure 4. Relationship between COD, BOD, TOC and DOC.

Table 8. Fate factors for pollutants in the wastewater input.

Overall fate of compounds (overload+treatment)	**Effluent (overflow)**	**Sludge**	**CO_2**	**Effluent (after treatment)**	**N-N_2**	**N-N_2O**
TOC	1.7%	64.7%	24.1%	9.5%		
COD	1.7%	60.0%	20.6%	17.7%		
BOD	1.6%	68.6%	21.9%	7.9%		
P-total (tertiary treatment scenario)	2.0%	94.1%		3.9%		
P-total (secondary treatment scenario)	2.0%	0.0%		98.0%		
SO_4	2.0%	0.0%		98.0%		
N-total (tertiary treatment scenario)	2.0%	10.6%		55.7%	31.5%	0.216%
N-total (secondary treatment scenario)	2.0%	10.6%		84.3%	3.1%	0.022%
Ag	1.3%	74.1%		24.7%		
Al	1.1%	94.0%		4.9%		
As	1.8%	21.6%		76.6%		
B	1.5%	49.3%		49.3%		
Ba	1.1%	94.0%		4.9%		
Be	1.5%	49.3%		49.3%		
Br	2.0%	0.0%		98.0%		
Ca	1.9%	9.8%		88.3%		
Cd	1.5%	49.3%		49.3%		
Cl	2.0%	0.0%		98.0%		
Co	1.5%	49.3%		49.3%		
Cr	1.5%	49.3%		49.3%		
Cu	1.3%	74.1%		24.7%		
F	2.0%	0.0%		98.0%		
Fe	1.5%	49.3%		49.3%		
Hg	1.3%	69.1%		29.6%		
I	2.0%	0.0%		98.0%		
K	2.0%	0.0%		98.0%		
Mg	1.9%	9.8%		88.3%		
Mn	1.5%	49.3%		49.3%		
Mo	1.5%	49.3%		49.3%		
Na	2.0%	0.0%		98.0%		
Ni	1.6%	39.4%		59.0%		
Pb	1.1%	89.0%		9.9%		
Sb	1.5%	49.3%		49.3%		
Sc	1.5%	49.3%		49.3%		
Se	1.5%	49.3%		49.3%		
Si	1.1%	94.0%		4.9%		
Sn	1.4%	58.2%		40.4%		
Sr	1.5%	49.3%		49.3%		
Ti	1.5%	49.3%		49.3%		
Tl	1.5%	49.3%		49.3%		
V	1.5%	49.3%		49.3%		
W	1.5%	49.3%		49.3%		
Zn	1.3%	69.1%		29.6%		

Source: Doka, 2007.

3.2.2. Fate of pollutants in sludge

The original model considers anaerobic digestion of mixed sludge. The amount of sludge formed is calculated from the TOC, N, S, and P initially present in wastewater, and the fate factors for sludge in table 8. For N and P, the calculations must take into account the share of secondary and tertiary treatment considered, 89% and 11%, respectively, since the amount of nitrogen and phosphorus in sludge depends on the treatment scenario.

The fate of these elements in anaerobic digestion is as follows:

- 60.3% of TOC and N goes to biogas.
- 22.3% of sulphur goes to biogas.

- All phosphorus, metals, as well as the remaining fractions of TOC, N, and S stay in digested sludge. For volatile metals, such as Arsenic or mercury, a small percentage may actually end up in biogas, but it is less than 1% and has not been taken into account.

With these factors the amount of digested sludge formed can be calculated. However, in this case, the final amount does consider the contribution of oxygen and hydrogen, which are calculated from the TOC in digested sludge by means of the following ratios: O/TOC = 0.55, and H/TOC = 0.125.

Since we have tracked the fate of each element in sludge, and the total amount produced, the elemental composition of the sludge can also be known. This is of especial relevance when the inventory of sludge application to agricultural soil must be determined. In fact, one of the outputs of the wastewater model as it is built in the excel spreadsheet, is the amount of these elements per kg sludge.

The biogas generated in anaerobic digestion is burned to produce heat and electricity. The compounds present in the exhaust gas are carbon dioxide, carbon monoxide, NMVOC, methane, nitrogen dioxide, ammonia, nitrous oxide, and nitrogen gas. The first four compounds are allocated on the basis of carbon present in the biogas to be burned, while the last four compounds are allocated on the basis of nitrogen present in the biogas to be burned. The proportion of carbon and nitrogen going into each one of these compounds is based on the typical fraction of these compounds as measured in Switzerland (Zimmermann et al. 1996), and is shown in tables 9 and 10. Sulphur in biogas, once incinerated gives raise to sulphur dioxide emissions, but we have assumed that our sulphur in the initial wastewater is dissolved, being found entirely in the effluent, and absent in the sludge.

Table 9. Fate factors for carbon in biogas.

Fate	**C-CO_2**	**C-CO**	**C-NMVOC**	**C-CH_4**
%	98.3%	0.2%	0.0069%	1.4%

Table 10. Fate factors for nitrogen in biogas

Fate	**N-NO_2**	**N-NH_3**	**N-N_2O**	**N-N_2**
%	5.6%	1.7%	0.9%	91.8%

In order to transform nitrogen and carbon to the corresponding chemical forms, the stoichiometric relationships must be established: 44g carbon dioxide/12 g TOC, 28 g carbon monoxide/12 g TOC, 16 g methane/12 g TOC, and for NMVOC, a ratio of 15 g NMVOC/12 g C is used. For nitrogen the relationships are: 46 g nitrogen oxide/14 g N, 17 g ammonia/14 g N, and 44 g nitrous oxide/14 g N.

3.2.3. Energy balance

Energy is used for several purposes in the plant, in form of electricity, light fuel, and natural gas. However, due to cogeneration with sludge biogas, the plant not only uses energy, but also produces both heat and electricity. The energy balance of the plant is calculated first by looking at the demand, then to the production, and finally to the difference between these.

The model considers the following energy demand factors:

- kWh/kg BOD removed in secondary treatment: 3.4
- kWh/kg COD removed in secondary treatment: 2.4
- kWh/kg TOC removed in secondary treatment: 7.0
- kWh/kg N removed (nitrified) in secondary or tertiary treatment: 10.5
- Miscellaneous (kWh/m^3 wastewater input): 0.028
- Digester (kWh/kg sludge input): 0.448
- Natural gas, sludge digestion (MJ/kg sludge input): 1.35

- Natural gas, miscellaneous (MJ/m^3 wastewater input): 0.0187
- Fuel light, sludge digestion (MJ/kg sludge input): 0.9977
- Fuel light, miscellaneous (MJ/m^3 wastewater input): 0.0138

The first four factors are related to aeration in the activated sludge tank. The first three are related to carbonaceous organic matter removal, and refer to the fraction of organic matter mineralised to carbon dioxide, not that gone to sludge. As it has already been stated before, these three parameters overlap. For this reason, instead of summing the three results, the model calculates the energy demand of carbonaceous organic removal as the average from these three calculation results. The fourth factor applies to all the nitrogen nitrified, regardless of whether this nitrification takes place in a plant with secondary or tertiary treatment (uncontrolled nitrification in the secondary treatment scenario is taken into account, as oxygen is actually consumed). There are some factors allocated to the amount of raw sludge entering the digester, and finally there are some energy demands which are not directly attributable to a particular process, and are allocated to the wastewater volume.

The amount of energy produced by cogeneration is calculated from the amount of carbon present in the biogas produced, using the following factors:

- Gross electricity production (kWh/kg carbon in biogas): 2.61

- Gross heat production (MJ/kg carbon in biogas): 40.2. By assuming an efficiency of 93% in a boiler or furnace, this figure is transformed to 43.2 MJ fuel equivalents/kg carbon in biogas. Since the average plant consumes 57% of the fuel energy as natural gas, and 43% as light fuel, the heat produced is equal to 25 MJ natural gas and 18.2 MJ light fuel per kg carbon in biogas.

In average operation, the fuel-equivalents produced by cogeneration are not enough to fulfil the plant's heat needs. Nevertheless, the allocation of energy production to a carbon-rich wastewater may result in the heat produced by cogeneration exceeding the fuel demand, giving rise to a net energy production. In this case we have followed the allocation rules of the Ecoinvent database, and no credit is given to the system for this avoided burden; instead, negative values are just converted to zero; This has been implemented in the excel spreadsheet and the GaBi software, by means of a parameterised calculation using a logical function.

3.2.4. Auxiliary materials and infrastructure

These include production of the sewer and the wastewater treatment, and chemicals for phosphorus removal in the tertiary treatment. They are allocated to wastewater as follows:

- Sewer grid: 2.18E-07 units/m^3
- Wastewater treatment plant infrastructure: 5.7E-09 units/m^3
- Iron chloride: 10.22 kg/kg P removed in tertiary treatment
- Iron sulphate: 7.47 kg/kg P removed in tertiary treatment
- Aluminium sulphate: 2.02 kg/kg P removed in tertiary treatment

Infrastructure is allocated on a wastewater volume basis, and the background inventory data for building a sewer and a wastewater treatment plant is shown in table 11. These data refer to the whole infrastructure (an entire sewer and an entire wastewater treatment plant), which are allocated to 1 m^3 of wastewater by means of the values above.

Table 11. Background inventory data for 1 sewer and 1 wastewater treatment plant (WWTP).

material/process	Sewer[a]	WWTP[b]	Units
Land use during construction	0	23100	m^2year
Land use during operation, vegetation	0	364000	m^2year
Land use during operation, built	0	328000	m^2year
Cast iron	8760	0	kg
Cement	142000	0	kg
Aluminium	0	33900	kg
Bitumen	0	19600	kg
Inorganic chemicals	0	19400	kg
Organic chemicals	0	159000	kg
Stainless steel	18000	243000	kg
Concrete	448	39000	m3
Diesel for construction machines	29400	0	MJ
Copper	0	36000	kg
Electricity	14300	1480	kWh
Excavated materials with hydraulic digger	5450	136000	m^3
Plastic extrusion	0	96200	kg
Glass fibre	0	76500	kg
Gravel	791000	0	kg
Limestone	0	837000	kg
Polyethylene high density	33300	95500	kg
Polypropylene	1890	0	kg
Polyvinylchloride	1660	0	kg
Polyethylene low density	0	628	kg
Reinforcement steel	51800	3030000	kg
Rock wool	0	34100	kg
Sand	445000	0	kg
Synthetic rubber	473	34500	kg
Tap water	15800000	4760000	kg
Transport by railroad	68900	2280000	tonkm
Transport by truck	85900	1920000	tonkm

[a] Based on data from Zimmermann et al. (1996).
[b] Based on data from Flückiger and Gubler (1994), Fahrner et al. (1995).

The use of chemicals can be calculated from the initial content of phosphorus in wastewater, the share of tertiary treatment (11%), and fate factor of phosphorus to sludge in tertiary treatment scenario (94%). As stated previously, using coagulants to remove phosphorus implies adding some substances to the wastewater stream. Table 12 shows the amount of these substances per kg of coagulant added. These factors are obtained as the percentage in weight that the cation or the anion represents in the overall molecular salt weight.

Table 12. Additional fluxes of substances due to P precipitation

Substance	Amount
Fe to sludge (kg/kg $FeCl_3$)	0.34
Cl to effluent (kg/kg $FeCl_3$)	0.66
Fe to sludge (kg/kg $FeSO_4$)	0.37
Sulphate to effluent (kg/kg $FeSO_4$)	0.63
Al to sludge (kg/kg $Al_2(SO4)_3$)	0.16
Sulphate to effluent (kg/kg $Al_2(SO4)_3$)	0.84

BOX 9. Inventory table for boiled broccoli wastewater treatment.

The table below shows the inputs and outputs for treating in a sewage treatment plant the wastewater (25 L) generated by broccoli excretion, as shown in box 8.

INPUTS	**Amount**	**Comments**
FROM TECHNOSPHERE		
Wastewater (L)	2.5E+01	Wastewater from broccoli excretion.
Inputs from wastewater treatment:		
Sewer grid infrastructure (units)	5.5E-09	Infrastructure for wastewater transport to WWTP.
WWTP infrastructure (units)	1.4E-10	Infrastructure for wastewater treatment plant.
Ferric chloride (kg)	6.8E-05	Coagulant for phosphorus precipitation.
Ferrous sulphate (kg)	4.9E-05	Coagulant for phosphorus precipitation.
Aluminium sulphate (kg)	1.3E-05	Coagulant for phosphorus precipitation.
Electricity (kWh/m^3)	1.2E-02	Net electricity demand including aeration, sludge digestion, and other miscellaneous demands.
Natural gas (MJ/m^3)	0.0E+00	Net natural gas demand including sludge digestion and other miscellaneous demands.
Light fuel oil (MJ/m^3)	0.0E+00	Net light fuel demand including sludge digestion and other miscellaneous demands.
OUTPUTS	**Amount**	**Comments**
TO NATURE		
Emissions to air from wastewater treatment:		
CO_2 (kg)	1.2E-02	Emission from carbonaceous organic matter degradation in biological treatment.
N_2O (kg)	3.1E-06	Emission from denitrification in biological treatment.
Emissions to air from biogas incineration:		
CO_2 (kg)	1.9E-02	Biogas burning.
CO (kg)	3.1E-05	Biogas burning.
NMVOC (kg)	4.7E-07	Biogas burning.
CH_4 (kg)	1.0E-04	Biogas burning.
NO_2 (kg)	5.5E-05	Biogas burning.
NH_3 (kg)	6.2E-06	Biogas burning.
N_2O (kg)	4.1E-06	Biogas burning.
TO TECHNOSPHERE		
Outputs from wastewater treatment:		
Toilet paper (kg)	7.8E-03	Present in wastewater. Removed in pre-treatment at wastewater treatment plant.
Sludge to other disposal routes (kg 37% dry mass)	3.3E-03	Sludge to landfill, incineration, or other disposal routes. This model does not include further transport and treatment of this sludge.
Sludge to agricultural soil (kg 6.7% dry mass)	7.4E-02	Sludge to landfarming. Modelling described in the next section.
TO NATURE		
Emissions to water from wastewater treatment:		
N-total (kg)	3.8E-03	From overflow discharge and treated effluent.
TOC (kg)	1.5E-03	From overflow discharge and treated effluent.
BOD (kg)	2.1E-03	From overflow discharge and treated effluent.
COD (g)	5.7E-03	From overflow discharge and treated effluent.
SO_4^{2-} (kg)	2.2E-03	From overflow discharge and treated effluent.
P-total (kg)	5.7E-05	From overflow discharge and treated effluent.
Cl (kg)	6.7E-05	From overflow discharge and treated effluent.
K (kg)	1.7E-04	From overflow discharge and treated effluent.
Na (kg)	1.3E-05	From overflow discharge and treated effluent.

3.3. Sludge treatment

The sludge treatment scenario has been made as representative as possible of the current UK conditions. It has not been possible to find complete UK statistics on biosolids treatment. The best data found on this topic have been extracted from the European Statistical Office (Eurostat, 2007c), which provides data for 2005 in England and Wales, and Northern Ireland (table 13). As an approximation to the overall treatment in the UK, it has been assumed that 75% of produced sludge is used in agriculture, 15% is incinerated, and 5% is landfilled.

Table 13. Urban wastewater production and disposal in England, Wales, and Northern Ireland in 2005 (million kg dry mass).

Sludge production and treatment	England and Wales	Northern Ireland
Total sludge production	1598.1	32.4
Agricultural use	1181.6	0.7
Compost and other applications	12	No data
Landfill	79.9	0.3
Dumping at sea	No data	0
Incineration	211.9	18.9
Others	112.7	12.5

Source: Eurostat (2007c).

3.3.1. Sludge applied to agricultural soil

The wastewater model has been designed to calculate the environmental burdens of agricultural use of sludge as a function of the user-defined wastewater generating the sludge. On the contrary, incineration and landfilling are independent of the wastewater input, and are modelled with an average sludge composition.

Sludge landfarming is also included in the original wastewater treatment model. The model includes sludge transport, and emissions of nitrogen and phosphorus to air and/or water. With regard to transport, the model assumes a moisture of 93.3%, which is transported along with the dry mass, and the average distance considered is 20 km. Sludge spreading in soil is modelled with the Ecoinvent dataset “Slurry spreading, by vacuum tanker”, allocated per m^3 sludge in fresh weight. In order to transform sludge weight to volume a sludge density of 1030 kg/m^3 is applied.

Concerning the fate of nitrogen and phosphorus in soil, the model assumes the following:

- 25.8% of applied nitrogen escapes to atmosphere as ammonia, and 1.2% as nitrous oxide. The remainder is assumed to be mainly absorbed by plants, or emitted as non-burdening nitrogen gas N_2.

- 2.01% of applied phosphorus is emitted to surface water as phosphate, while 0.57% is emitted to groundwater. The remainder is assumed to be taken up by plants (system cut-off).

In a similar way as it has been done in the WWTP heat energy balance, the system does not receive any credit for additional functions, in this case for supplying an agricultural system with a fertiliser. The food system is simply cut-off.

With regard to carbon applied to soil, it will be slowly mineralised and released to the atmosphere as carbon dioxide. According to a study commissioned by the European Commission, in a 100 year period, which is the standard for greenhouse gas emission assessments, 92% of the carbon applied in soil as compost will be emitted to atmosphere, while the remaining 8% is stored in soil (Smith et al., 2001). We have used these fate factors in the model for sludge.

In terms of land use, sludge application to agricultural soil is not charged any burden for land occupation because such burden is fully ascribed to the agricultural land use. Any potential effects on soil quality derived from e.g. increased/reduced soil organic carbon is also ascribed to agriculture.

Finally, metals initially present in sludge are inventoried as final emissions to soil, without further fate modelling.

BOX 10. Inventory table for boiled broccoli sludge application to agricultural soil.

The table below shows the inventory for applying to agricultural soil the amount of sludge produced by the sewage treatment plant after treating the wastewater from broccoli excretion.

INPUTS	**Amount**	**Comments**
FROM TECHNOSPHERE		
Sludge in fresh weight (kg)	7.4E-02	Sludge allocated to broccoli excretion.
Truck (kgkm)	1.5E+00	Transport of sludge to farm.
Slurry spreading (m^3)	7.2E-05	Spreading of sludge on soil.
OUTPUTS	**Amount**	**Comments**
TO NATURE		
Emissions to air:		
NH_3 (kg)	4.9E-05	Loss of nutrients from soil to the atmosphere.
N_2O (kg)	5.9E-06	Loss of nutrients from soil to the atmosphere.
CO_2 (kg)	9.5E-03	Oxidation of organic matter from soil in a period of 100 years.
Emissions to water:		
PO_4 groundwater (kg)	9.4E-08	Leaching of nutrients from soil.
PO_4 river water (kg)	3.3E-07	Leaching of nutrients from soil.
Emissions to soil:		
TOC (kg)	2.3E-04	Carbon stored in soil after 100 years.
Al (kg)	2.1E-06	Metal from phosphorus precipitation agent.
Fe (kg)	4.2E-05	Metal from phosphorus precipitation agent.

3.3.2. Sludge to incineration and landfilling

Disposal of sludge by means of incineration and landfilling is not included in this model. The excel spreadsheet only calculates the amount of sludge to be treated by these disposal options (see box 10), which in turn depends on the sludge treatment scenario introduced. The default is representative of the UK, where approximately 15% of the sludge is incinerated and 5% landfilled. Nevertheless, the user can modify this scenario.

These disposal routes require the sludge to have a higher concentration of dry mass. Doka's model considers 37% dry mass for transporting the sludge, being the distance to the respective plants of 10 km. For both incineration and landfilling, the elemental composition considered for sludge in the RELU case studies is that proposed by Doka (2007) as obtained with his wastewater treatment model with average Switzerland wastewater. From a UK perspective this is may seem acceptable, due to the relatively low percentage of sludge disposed of in incinerators and landfills. Nonetheless, in regions where these disposal routes are dominant, a more detailed modelling should be addressed. In such a case, an appropriate option would be to obtain waste-specific inventories from the excel spreadsheets for landfilling and incineration included in the Ecoinvent database (Doka 2003).

4. UNCERTAINTY

In LCA, inventory data for processes is usually described by means of single figures, the mean values. These values involve a certain degree of uncertainty. Different types of uncertainty can be present in inventory data (Frischknecht et al., 2004):

- Variability and stochastic error due to measurement uncertainty, temporal variations, etc.
- Appropriateness of datasets used, such as approximating the electricity profile of a country using another country's profile.
- Model uncertainty, such as using linear relationships to describe a process which actually is not linear.
- Omission of inventory flows due to lack of data.

In this model an attempt has been made to include the first kind of uncertainty, in a quantitative way. The goal of this uncertainty assessment is to offer an uncertainty range for the most environmentally relevant inventory results, i.e. all of them with the exception of the following flows related to human metabolism:

- Oxygen consumption.
- Water emissions to air.
- Heat emissions to air.

The uncertainty ranges include the uncertainty derived from the model itself, but not from the food composition. The food constituents are assigned by default no uncertainty at all, although the excel spreadsheet is designed to allow the user to introduce uncertainty values if desired. In addition, the user is also allowed to modify the default uncertainties of the parameters related to toilet use.

With regard to the probability distribution function considered, the lognormal distribution is increasingly used in LCA to describe uncertainty, as it has been suggested to be a more realistic approximation for the distribution of chemicals in the environment, as compared to the normal distribution (Hoftstetter, 1998). The lognormal distribution is currently the default choice by Ecoinvent, one of the most popular LCA databases. It is arguable whether or not the lognormal distribution is actually more representative than the normal distribution for some of the model parameters, specially those referring to toilet use (consumption of auxiliary materials and energy use, both closely related to consumer behaviour). In a case study on the environmental impact of incineration, Sonneman et al. (2002) considered a lognormal distribution for emissions to the environment, and a normal distribution for some parameters like the electricity production and the number of working hours. Nevertheless, the uncertainty assessment in the model has been entirely based on the lognormal distribution. For further information on the latter see Limpert et al. (2001).

Uncertainty in lognormal distributions is often expressed using the square of the geometric standard deviation (σ_g^2), which gives a confidence interval of 95%. The squared geometric standard deviation (σ_g^2) can be considered as an 'uncertainty factor'. An uncertainty factor of 1 means no uncertainty at all, while an uncertainty factor of 1.5 means that, for a parameter with a mean value of 2, the 95% confidence interval is in the range of:

2 x 1.5 = 3 (upper boundary value, or 97.5% cumulated probability that the true value is below 3).
2 / 1.5 = 1.33 (lower boundary value, or 2.5% cumulated probability that the true value is below 1.33).

Given a set of values for a given parameter (v_1, v_2, v_3, … v_n), σ_g^2 is calculated with equation 11:

$$\sigma_g^2 = \left(e^{\sqrt{\frac{\sum_{i=1}^{n} (\ln v_i - \ln \mu_g)^2}{n}}} \right)^2 \qquad [11]$$

Where μ_g is the geometric mean.

4.1. Estimation of uncertainty for human excretion parameters

The main problem encountered when uncertainty has to be quantified for a system in LCA is actually the lack of uncertainty data for the variables describing the system. Often the only information available in the inventory analysis are the mean values, and since these values are not the direct result of measurements, but are obtained from literature data, expert judgement, or estimations, little or no information at all is available on uncertainty.

The uncertainty related to the data used in the excretion part of the model (table 14) has been estimated in several ways, which can be summarised as follows:

- Calculation from a sample: for some parameters a (more or less) representative sample has been obtained, allowing the calculation of a proper σ_g. The uncertainty for most of the elemental composition parameters has been determined in this way.
- Calculation from a maximum-minimum range: in some cases, besides the mean, only upper and lower values have been found. In these cases uncertainty is determined from these three values. Most of the fate factors have been assigned a σ_g value in this way.
- Qualitative judgement: unfortunately, in many cases not even upper and lower values are found. In these cases, either a max.-min. range has been qualitatively defined in order to calculate σ_g, or a σ_g has been just assigned.

In any case, this uncertainty assessment must be considered as a very coarse estimation, aimed only at giving a quantitative glimpse to the order of magnitude of uncertainty in the model results.

Table 14. Uncertainty for parameters used in the human excretion part of the model.

Parameters	σ_g	Comments
ELEMENTAL COMPOSITION OF FOOD CONSTITUENTS		
Carbon content in protein	1.24	Calculated from the carbon content of the 20 amino acids.
Carbon content in fat	1.02	Calculated as the variability of a triglyceride with 16 C fatty acids to a triglyceride with 20 C fatty acids.
Carbon content in carbohydrate	1.03	Calculated from the carbon content of the individual compounds taken into account for calculating the composition of carbohydrates.
Carbon content in alcohol	1.00	Uncertainty assumed as zero, since ethanol is a single compound defined by its empirical formula.
Carbon content in organic acids	1.00	Uncertainty assumed as zero. It is assumed that this category will be represented by acetic acid and/or lactic acid, which have the same carbon content.
Hydrogen content in protein	1.22	Calculated from the carbon content of the 20 amino acids.
Hydrogen content in fat	1.22	Assumption. The uncertainty is considered higher than for carbon, as triglycerides can contain saturated and non-saturated fatty acids.
Hydrogen content in carbohydrate	1.02	Calculated from the carbon content of the individual compounds taken into account for calculating the composition of carbohydrates.
Hydrogen content in alcohol	1.00	Uncertainty assumed as zero, since ethanol is a single compound defined by its empirical formula.
Hydrogen content in organic acids	1.00	Uncertainty assumed as zero. It is assumed that this category will be represented by acetic acid and/or lactic acid, which have the same carbon content.
Carbon content in faeces	1.12	The carbon content ranges from 44% to 55% (Feachem et al., 1983).
Carbon content in organic non-degradable material	1.19	Calculated from the carbon content in cellulose (44%) and the carbon content of lignine (62%).The figure for lignine is from Philips and Goss (1936).
Nitrogen content in protein	1.07	Calculated from the variability of nitrogen content in proteins from different food types (Food Standards Agency, 2002).
Sulphur content in protein	1.55	Calculated from the N/S ratio of a big sample of food products, including fruits, vegetables, meat, and fish (Masters and mcCance, 1939).
FATE FACTORS		
Fate of inorganic compounds in food	1.00	Assumption. The uncertainty of this parameter is considered to be low.
Fraction of water to faeces	1.06	Variability of the fate factor when the amount of urine is changed from 1.5 L/person/day to 1.2 L/person/day. The latter is extracted from Feachem et al. (1983).
Fraction of water to urine	1.04	Variability of the fate factor when the amount of urine is changed from 1.5 L/person/day to 1.2 L/person/day. The latter is extracted from Feachem et al. (1983).
Fraction of degradable carbon to CO_2	1.04	Variability of the fate factor when taking the range 143-247 g C exhaled/person/day, as shown in table 3.
Fraction of degradable carbon to faeces	1.29	Variability of the fate factor when taking the range 143-247 g C exhaled/person/day, as shown in table 3.
Fraction of Nitrogen to urea	1.12	The lowest figure considered for this fate factor is 80% (for a urine production of 1.2 L/person/day), although the model considers 100%. As a rough estimation these two values are used for the calculation.
Fraction of sulphur to sulphate	1.00	Assumption. The uncertainty of this parameter is considered to be low, since sulphur is mostly emitted as sulphate (Florin et al., 1991).
Fraction of fibre to faeces	1.00	Assumption. The uncertainty of this parameter is considered to be low.
Fraction of degradable carbon to methane	1.70	Variation in the fate factor when the maximum and minimum values in methane production, according to experimental data in Bond et al. (1971), are taken into account. The uncertainty in the percentage of methane producers in the population is not assessed.
Fraction of non-degradable carbon to methane	1.70	Same value as for degradable organic material to methane.
Amount of daily urine production	1.12	Maximum and minimum urine production is taken as 1.2-1.5 L/person/day.
Amount of daily faeces production	1.31	Variability from several UK studies cited in Feachem et al. (1983).

Table 14. continued.

Parameters	σ_g	Comments
TOILET USE PARAMETERS		
TOC/BOD ratio	1.41	Uncertainty unknown. This value is a rough estimation
TOC/COD ratio	1.41	Uncertainty unknown. This value is a rough estimation.
Toilet paper consumption per person per day	1.17	Calculated from the variability in the average consumption in different European countries according to the European Tissue Symposium (2005).
Toilet flush volume	1.31	The uncertainty is calculated assuming as maximum value 12 L, and as minimum value 7 L.
Hand washing volume	1.73	Uncertainty unknown. This value is obtained assuming as maximum and minimum values 3 and 1 L.
Soap consumption per use	1.39	Uncertainty in measurement is very low. The uncertainty is judged to be mostly represented by the choice to push once or twice the soap dispenser. The latter is used to calculate the uncertainty factor.
Toilet uses per day	1.53	The uncertainty is calculated assuming as maximum value 7, and as minimum value 3 L.
Share of toilet use at home	1.26	The uncertainty is calculated assuming as maximum value 80%, and as minimum value 50%.
Share of toilet use at work	1.58	The uncertainty is calculated assuming as maximum value 50%, and as minimum value 20%.
Power of hot air blower	1.35	Calculated from the different products in the catalog of Handryers.net (2005). Assuming just one drying cycle.
Time to dry hands	1.44	Calculated from the different products in the catalog of Handryers.net (2005). Assuming just one drying cycle.
Towel weight	1.73	Uncertainty unknown. This value is a rough estimation.
Number of persons per household	1.00	Uncertainty unknown. Assumed as zero.
Frequency of towel washing	1.73	Uncertainty unknown. This value is a rough estimation.
Power demand of washing machine	1.07	Calculated from the average of different European countries, according to Group for Efficient Appliances (1995).
Detergent use in washing machine	1.73	Uncertainty unknown. This value is a rough estimation.
Water use in washing machine	1.07	Uncertainty unknown. This value assumes the same uncertainty than that for energy consumption of washing machines.
Power demand of drier	1.11	Calculated from the average of different European countries, according to Group for Efficient Appliances (1995).
Laundry wastewater, COD content	1.46	Calculated from the averages reported in Eriksson et al. (2002).
Laundry wastewater, BOD content	2.14	Calculated from the averages reported in Eriksson et al. (2002).
Laundry wastewater, N content	3.20	Calculated from the averages reported in Eriksson et al. (2002).
Laundry wastewater, P content	2.16	Calculated from the averages reported in Eriksson et al. (2002).
Basin wastewater, COD content	2.00	Calculated from the averages reported in Eriksson et al. (2002).
Basin wastewater, BOD content	1.49	Calculated from the averages reported in Eriksson et al. (2002).
Basin wastewater, N content	2.26	Calculated from the averages reported in Eriksson et al. (2002).
Basin wastewater, P content	4.84	Calculated from the averages reported in Eriksson et al. (2002).

4.2. Estimation of uncertainty for wastewater and sludge treatment parameters

The original wastewater and sludge treatment model by Doka already included an uncertainty assessment, based as well on a lognormal probability density function and the square of the geometric standard deviation as uncertainty factor. Most of the uncertainty factors shown in table 15 have been taken from that original model as well.

Table 15. Uncertainty factors for wastewater and sludge treatment parameters.

Parameters	σ_g	Comments
WASTEWATER TREATMENT		
Share of secondary or secondary plus tertiary treatment scenarios	See comments	Calculated with the following formula: $\sigma_g = (-0.05 \cdot \ln \text{share}) + 1$ Where share is the share of each scenario. This calculation was not included in the original model by Doka, since there were no such scenarios.
Fate factors for overflow discharge, wastewater treatment removal, and raw to digested sludge	See comments	Calculated with the following formula: $\sigma_g = (-0.0346 \cdot \ln \text{FF}) + 1$ Where FF is the mean value of the fate factor, expressed in kg/kg.
Fate factors for carbon and nitrogen in biogas incineration	See comments	Calculated with the following formula: $\sigma_g = (-0.05 \cdot \ln \text{FF}) + 1$ Where FF is the mean value of the fate factor, expressed in kg/kg.
Electricity demand factors per kg BOD, COD, TOC, N removal, and sludge to be digested	1.00	Uncertainty for electricity demand is calculated as a function only of the uncertainty related to the amount of BOD, COD, TOC, and N removed, and sludge to be digested.
Natural gas and light fuel demands per kg sludge to be digested	1.00	Uncertainty for fuel demand is calculated as a function only of the uncertainty related to the amount of sludge to be digested.
Electricity, natural gas, and light fuel demand per m^3 wastewater, for miscellaneous uses	1.05	Estimated uncertainty.
Gross electricity and heat produced by cogeneration, per kg carbon in biogas	1.00	Uncertainty for electricity and heat production is calculated as a function only of the uncertainty related to the amount of carbon in biogas.
Demand of coagulants per kg P removed	1.03	Estimated uncertainty.
Additional fluxes of cations and anions due to coagulant use, per kg coagulant	1.00	The uncertainty of these substances will be related to coagulant demand.
Allocation of sewer and WWTP infrastructure per m^3 wastewater	1.00	The uncertainty of the processes and materials involved in infrastructure is heeded in the corresponding Ecoinvent datasets.
SLUDGE TREATMENT		
Share of sludge to agricultural soil, landfill, and incineration	See comments	Calculated with the following formula: $\sigma_g = (-0.05 \cdot \ln \text{share}) + 1$ Where share is the share of sludge to a given disposal route.
Sludge density	1.00	Not heeded.
Sludge moisture as applied to soil	1.00	Not heeded.
Transport distance to farm	1.00	Not heeded. The uncertainty of the transport operation is a function only of the uncertainty related to the amount of sludge produced.
Slurry spreader use per m^3 sludge	1.00	Not heeded. The uncertainty of the spreading operation is a function only of the uncertainty related to the amount of sludge produced.
Fate factors for N emissions from soil	1.73	Based on a variability of fate factors values from 10% to 90%.
Fate factors for P emissions from soil	1.25	Data from Volker Prashun, FAL.
Fate factor for C to CO_2 emissions from soil	1.02	Calculated from a minimum value of 91% and a maximum value of 94% carbon emitted to atmosphere as carbon dioxide after 100 years (Smith et al. 2001).
Fate factor for C stored in soil	1.22	Calculated from a minimum value of 6% and a maximum value of 9% carbon stored in soil after 100 years (Smith et al. 2001).

4.3. Uncertainty propagation

Once the uncertainty of the model parameters is determined, the uncertainty of the final results is calculated by means of error propagation equations. Basically four types of calculations are involved in the model: sums, multiplications, divisions, and subtractions. The equations for error propagation are the same as used in the Ecoinvent report for waste treatment services (Doka, 2003).

Given two mean values, a and b, the square of the geometric standard deviation ($\sigma^2_{g\ axb}$) of the operation axb, is calculated with equation 12:

$$\sigma^2_{g\,axb} = \left(e^{\sqrt{(\ln \sigma_{ga})^2 + (\ln \sigma_{gb})^2}} \right)^2 \qquad [12]$$

Where σ_{ga} and σ_{gb} are the geometric standard deviations of a and b, respectively. The square of the geometric standard deviation ($\sigma^2_{g\ a/b}$) of the operation a/b, is calculated with equation 13:

$$\sigma^2_{g\,a/b} = (\sigma_{g\,a} \cdot \sigma_{g\,b})^2 \qquad [13]$$

The square of the geometric standard deviation ($\sigma_g{}^2{}_{a+b}$) of the operation a+b, is calculated with equation 14:

$$\sigma^2_{g\,a+b} = \left(e^{\sqrt{\ln\left(\frac{Var_{a+b}}{\mu^2{}_{a+b}}+1\right)}} \right)^2 \qquad [14]$$

Where Var_{a+b} and μ_{a+b} are the arithmetic variance and arithmetic mean of the operation, which are in turn calculated with equations 14 and 15:

$$Var_{a+b} = \left(a^2 \cdot e^{(\ln \sigma_{ga})^2} \cdot \left(e^{(\ln \sigma_{ga})^2} - 1 \right) \right) + \left(b^2 \cdot e^{(\ln \sigma_{gb})^2} \cdot \left(e^{(\ln \sigma_{gb})^2} - 1 \right) \right) \qquad [15]$$

$$\mu_{a+b} = \left(a \cdot e^{\frac{(\ln \sigma_{ga})^2}{2}} \right) + \left(b \cdot e^{\frac{(\ln \sigma_{gb})^2}{2}} \right) \qquad [16]$$

Finally, for the operation a – b, $\sigma_g{}^2{}_{a\text{-}b}$ is calculated with equation 17:

$$\sigma^2_{g\,a-b} = \left(\frac{(a \cdot \sigma^2_{g\,a}) - b}{a - b} \right) \qquad [17]$$

BOX 11. Uncertainty of carbon dioxide emissions from boiled broccoli excretion

Carbon dioxide emissions from human metabolism are calculated in box 4 as 80 g per kg boiled broccoli. The uncertainty of this value depends on the following parameters:

- Amount of degradable organic material in broccoli (σ_g = 1.00*)
- Carbon content in degradable organic material, which in turn depends of:
  - Amount of protein (σ_g = 1.00*) and carbon content of protein (σ_g = 1.24)
  - Amount of fat (σ_g = 1.00*) and carbon content of fat (σ_g = 1.02)
  - Amount of carbohydrate (σ_g = 1.00*) and carbon content of carbohydrate (σ_g = 1.03)
- Fate factor for degradable organic carbon to carbon dioxide (σ_g = 1.04)

* The uncertainty of food composition is not taken into account in the model.

First, the uncertainty of the carbon content in degradable organic material is calculated with equations 14, 15, and 16 (see table below). The mean values in the table correspond to the contribution of each food constituent to the total carbon content in degradable organic material, as calculated in box 2.

Carbon content in organic degradable material	σ_g	Mean	Arithmetic mean	Arithmetic variance
Carbon from protein	1.24	0.29	0.30	4.15E-03
Carbon from fat	1.02	0.12	0.12	5.93E-06
Carbon from carbohydrate	1.03	0.09	0.09	7.42E-06
Total carbon in degradable organic material	1.13	0.50	0.51	4.17E-03

Finally, the uncertainty for carbon dioxide emissions is calculated with equation 12 taking into account the geometric standard deviation of the contributing parameters, 1.13 for the carbon content in degradable organic matter, and 1.04 for the fate factor:

$$\sigma^2_{g\ axb} = \left(e^{\sqrt{(\ln 1.13)^2 + (\ln 1.04)^2}} \right)^2 = 1.30$$

Therefore, the carbon dioxide emissions per kg of boiled broccoli are in the following range (95% confidence interval):

80 g x 1.30 = 104 g
80 g / 1.30 = 62 g

5. INTERPRETATION

5.1. Overall inventory

The excel spreadsheet allows the user to obtain the following results:

- An inventory table for human excretion (worksheet 'Excretion inventory')

- Two tables showing the composition of the wastewater from human excretion and the composition of wastewater sludge (worksheet 'WW and sludge composition')

- An inventory table including both human excretion, wastewater treatment, and wastewater sludge application to soil (worksheet 'Overall inventory').

The latter is shown in box 12 for the broccoli case study, displaying also the final uncertainty factors for each flow. In this table, intermediate flows to technosphere, like wastewater volume, or weight of sludge applied to soil, are not shown, since these flows are converted in this table to their corresponding exchanges with the technosphere or with nature. Flows from human excretion with low environmental relevance, namely oxygen intake, heat emissions, and water emissions from respiration are not shown either, but they can be seen in the specific inventory table for human excretion.

BOX 12. Overall inventory for boiled broccoli excretion and wastewater treatment

INPUTS	Amount	Uncertainty	Comments
FROM TECHNOSPHERE			
Boiled broccoli	9.9E+02	$\sigma_g^2 =$ 1.0	g food ingested.
Inputs from human excretion:			
Toilet paper (kg)	7.8E-03	$\sigma_g^2 =$ 1.7	Allocated on the basis of solid+liquid excreta mass.
Tap water (L)	2.4E+01	$\sigma_g^2 =$ 2.7	Toilet flushing plus hand washing, plus towel washing, allocated on the basis of solid+liquid excreta mass.
Soap (kg)	6.5E-03	$\sigma_g^2 =$ 3.6	Hand washing, allocated on the basis of solid+liquid excreta mass.
Detergent (kg)	3.6E-04	$\sigma_g^2 =$ 7.7	Detergent for washing machine used for towel washing which in turn has been used to wash hands.
Electricity (kWh)	2.3E-02	$\sigma_g^2 =$ 3.6	Electricity for hot air blower, washing machine and drier. All these processes are related to hand drying.
Inputs from wastewater treatment:			
Sewer grid infrastructure (units)	5.5E-09	$\sigma_g^2 =$ 2.7	Infrastructure for wastewater transport to treatment plant.
Wastewater treatment plant infrastructure (units)	1.4E-10	$\sigma_g^2 =$ 2.7	Infrastructure for wastewater treatment plant.
Ferric chloride (kg)	6.8E-05	$\sigma_g^2 =$ 3.4	Coagulant for phosphorus precipitation.
Ferrous sulphate (kg)	4.9E-05	$\sigma_g^2 =$ 3.4	Coagulant for phosphorus precipitation.
Aluminium sulphate (kg)	1.3E-05	$\sigma_g^2 =$ 3.4	Coagulant for phosphorus precipitation.
Electricity (kWh/m^3)	1.2E-02	$\sigma_g^2 =$ 1.5	Net electricity demand including aeration, sludge digestion, and other miscellaneous demands. Electricity production by cogeneration with biogas is subtracted.
Natural gas (MJ/m^3)	0.0E+00	$\sigma_g^2 =$ 1.0	Net natural gas demand including sludge digestion and other miscellaneous demands. Heat production by cogeneration with biogas is subtracted.
Light fuel oil (MJ/m^3)	0.0E+00	$\sigma_g^2 =$ 1.0	Net light fuel demand including sludge digestion and other miscellaneous demands. Heat production by cogeneration with biogas is subtracted.
Inputs from sludge application to agricultural soil:			
Lorry (kgkm)	1.5E+00	$\sigma_g^2 =$ 1.2	Transport of sludge to farm.
Slurry spreading (m^3)	7.1E-05	$\sigma_g^2 =$ 1.2	Spreading of sludge on soil.
OUTPUTS	**Amount**	**Uncertainty**	**Comments**
TO NATURE			
Emissions to air from human excretion:			
CO_2 (kg)	8.0E-02	$\sigma_g^2 =$ 1.3	Produced by catabolism of degradable constituents in food (carbohydrates, fat, and protein).
CH_4 (kg)	2.0E-05	$\sigma_g^2 =$ 2.4	Produced by colonic bacteria. Degradation of all carbon-containing compounds, including fibre.
Emissions to air from wastewater treatment:			
CO_2 (kg)	1.2E-02	$\sigma_g^2 =$ 1.3	Emission from carbonaceous organic matter degradation in biological treatment.
N_2O (kg)	3.1E-06	$\sigma_g^2 =$ 1.5	Emission from denitrification in biological treatment.
Emissions to air from biogas incineration:			
CO_2 (kg)	1.9E-02	$\sigma_g^2 =$ 1.3	Biogas burning.
CO (kg)	3.1E-05	$\sigma_g^2 =$ 1.8	Biogas burning.
NMVOC (kg)	4.7E-07	$\sigma_g^2 =$ 2.3	Biogas burning.
CH_4 (kg)	1.0E-04	$\sigma_g^2 =$ 1.6	Biogas burning.
NO_2 (kg)	5.5E-05	$\sigma_g^2 =$ 1.5	Biogas burning.
NH_3 (kg)	6.2E-06	$\sigma_g^2 =$ 1.6	Biogas burning.

N_2O (kg)	4.1E-06	σ_g^2 =	1.7	Biogas burning.
Emissions to air from sludge application to soil:				
NH_3 (kg)	4.9E-05	σ_g^2 =	3.1	Loss of nutrients from soil to the atmosphere.
N_2O (kg)	5.9E-06	σ_g^2 =	3.1	Loss of nutrients from soil to the atmosphere.
CO_2 (kg)	9.5E-03	σ_g^2 =	1.3	Oxidation of organic matter from soil in a period of 100 years.
TO TECHNOSPHERE				
Outputs from wastewater treatment:				
Toilet paper (kg)	7.8E-03	σ_g^2 =	1.7	Present in wastewater. Removed in pretreatment at wastewater treatment plant.
Sludge to other disposal routes (kg 37% dry mass)	3.3E-03	σ_g^2 =	1.3	Sludge to landfill, incineration, or other disposal routes. This model does not include further transport and treatment of this sludge.
TO NATURE				
Emissions to water from wastewater treatment:				
N-total (kg)	3.8E-03	σ_g^2 =	1.3	From overflow discharge and treated effluent.
TOC (kg)	1.5E-03	σ_g^2 =	1.3	From overflow discharge and treated effluent.
BOD (kg)	2.1E-03	σ_g^2 =	1.9	From overflow discharge and treated effluent.
COD (g)	5.7E-03	σ_g^2 =	1.9	From overflow discharge and treated effluent.
SO_4^{2-} (kg)	2.2E-03	σ_g^2 =	2.3	From overflow discharge and treated effluent.
P-total (kg)	5.7E-05	σ_g^2 =	3.2	From overflow discharge and treated effluent.
Cl (kg)	6.7E-05	σ_g^2 =	2.4	From overflow discharge and treated effluent.
K (kg)	1.7E-04	σ_g^2 =	1.0	From overflow discharge and treated effluent.
Na (kg)	1.3E-05	σ_g^2 =	1.0	From overflow discharge and treated effluent.
Emissions to water from sludge application to soil:				
PO_4^{3-} to groundwater (kg)	9.4E-08	σ_g^2 =	3.6	Leaching of nutrients from soil.
PO_4^{3-} to river water (kg)	3.3E-07	σ_g^2 =	3.6	Leaching of nutrients from soil.
Emissions to soil from sludge application to soil:				
TOC (kg)	2.3E-04	σ_g^2 =	1.6	Carbon stored in soil after 100 years.
Al (kg)	2.1E-06	σ_g^2 =	3.4	Element emitted to soil.
Fe (kg)	4.2E-05	σ_g^2 =	2.5	Element emitted to soil.

5.2. Discussion

The following discussion is focused only on the processes described in this document. It is of course interesting to put this model and the results obtained in the context of a complete life cycle, but this is not included here. For such a discussion, please see the following paper:

Muñoz I, Milà i Canals L, Clift R. *Consider a spherical man - An allocation model for human excretion in Life Cycle Assessment of Food products*. Submitted.

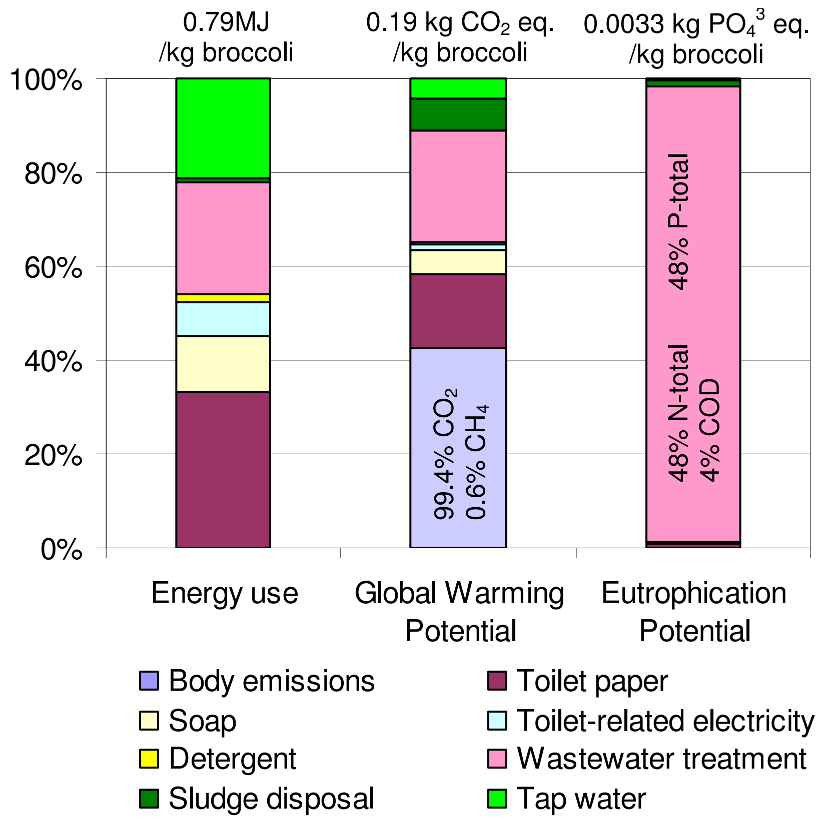
5.2.1. Impact assessment

Box 13 shows the results of characterisation applied to human excretion and wastewater-sludge treatment for 1 kg broccoli. The background system has been entirely modelled using the Ecoinvent database, including also the disposal share of sludge to landfill and incineration. The characterisation models used are those by the CML version 2001 (Guinée et al. 2002). For this result screening, only three impact categories have been assessed: Global Warming Potential (GWP), Energy Use (EU), and Eutrophication Potential (EP).

From an Energy Use point of view, it is interesting to see that the technosphere processes related to toilet use (toilet paper, tap water, etc.) have a larger contribution than those related to wastewater treatment. Approximately 75% of the overall EU is related to the toilet, mainly due to tissue paper (33%) and tap water production (21%).

Global Warming Potential offers a different picture, as carbon emissions from the human body make their appearance. Body emissions account for 43% of the overall GWP, with carbon dioxide being responsible of almost all this contribution; methane emissions from the human body represent less than 1% of the body's GWP for broccoli. It must be noted, however, that biogenic emissions – specially carbon dioxide – are not always taken into account in LCIA, as they are assumed to be offset in the agricultural stage by carbon fixation during photosynthesis. In the RELU project all carbon emissions, regardless of their fossil or biogenic origin, have been included in LCIA: as negative emissions for biomass fixation, and as positive emissions when carbon is released, as is the case for human excretion.

BOX 13. Impact assessment for broccoli excretion and wastewater treatment



The second most important process in GWP is wastewater treatment (24%), as it is at this stage that most of the carbon in human liquid and solid excreta is released, during biological treatment and anaerobic digestion of sludge. It is interesting to observe the relatively high contribution of toilet paper production (16%). Finally, the release of carbon as carbon dioxide in agricultural soils only represents 6% of the total emissions. This low contribution is in part explained by the fact that 60% of the initial carbon in raw sludge is released during anaerobic digestion in the sewage treatment plant.

With regard to EP, the emissions at the wastewater treatment stage are dominant, as is usual in LCA of wastewater systems (Roeleveld et al. 1997, Hospido et al. 2004), and also in food LCA studies where the fate of nutrients in food has been taken into account (Sonesson et al. 2004; Ziegler et al. 2003). Emissions from the wastewater treatment plant account for 98% of the total EP, with a clear dominance of nitrogen and phosphorus compounds present in the treated effluent. The contribution of other subsystems is irrelevant.

The results for GWP and EP show that emissions from the human body – either emitted directly, or indirectly after the wastewater treatment stage – are very relevant in the end-of-life phase of food products. Nevertheless, this relative importance may change from one product to another: beverages, with low dry matter content, involve lower emissions of EP and GWP contributing substances, while foodstuffs with a higher dry matter content involve higher emissions (Muñoz et al. submitted).

5.2.2. Uncertainty

Quantitative uncertainty assessments are seldom included in conventional LCA studies. Probably one of the reasons is the additional effort these require, as learned from this model. Considerable effort is needed in collecting data variability, as well as in propagating the uncertainty through the calculations. The uncertainty assessment implemented in the model is probably far from satisfactory, but it gives a quantitative idea of whether some inventory results are more reliable than others. The uncertainty factors shown in box 12, expressed as the squared geometric standard deviation (σ_g^2), range from 1 to 7.7. Flows with an uncertainty of 1 are unrealistic (with the exception of the input broccoli, and also those flows which have a mean value of zero), meaning that uncertainty data has not been included in the model or it is missing. It is in fact very likely that these final uncertainty values are underestimated. The most uncertain flows are those related to toilet use, such as detergent, soap, and electricity, due to the fact that the calculation of the final inventory value involves many intermediate parameters, the uncertainty of which propagates through the calculations. Phosphorus-related flows (emissions and precipitation agents consumption) also show a high uncertainty, and the reason is that a small fraction of the input phosphorus to the system, namely that from toilet basin wastewater, has a σ_g of 4.8 (σ_g^2 = 23!!), the highest in the model, which propagates to the final result with σ_g^2 values above 3 for the different related flows.

However, the positive message from this uncertainty assessment is that, when the uncertainty factors in the inventory are put in the context of the impact assessment – which actually also introduces uncertainty, although this has not been tackled so far by the LCA community –, we see that the most critical flows, such as carbon dioxide emissions, N-total emissions, and toilet paper, tend to be among the least uncertain results (σ_g^2 <2).

What has been discussed here is the model uncertainty. Nevertheless, an issue remaining for discussion, which is out of the scope of this document, is the potential contribution to uncertainty from uncertainty in the food composition. This is something the model users can find out with their own data, since the spreadsheet is prepared to propagate this uncertainty to the final inventory results.

5.2.3. Conclusions and outlook

The model presented in this document provides food LCA practitioners with a practical tool to include in their studies human excretion, a life cycle stage almost systematically omitted up to date. Exclusion of this group of processes may be justified, depending on the goal of the study, but when it comes to identify the life cycle hotspots, as well as to close the balance of materials in the life cycle, or even to compare differences in emissions from different food types, this tool may be useful.

The model is based in very simple – but plausible – assumptions, and can be considered reliable when an overall balance of the major constituents in food is to be done. The fate of very specific food constituents, such as vitamins, or cholesterol, is not heeded, and the occurrence and fate of toxic organic compounds, such as pesticides, has been excluded. Another excluded, but interesting issue, is the availability of carbohydrates as a function of industrial processing/cooking. All these subjects could be subject of further model sophistication.

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