THE MODELLING OF AN ANAEROBIC DIGESTION PLANT AND A SEWAGE PLANT IN THE ORWARE SIMULATION MODEL

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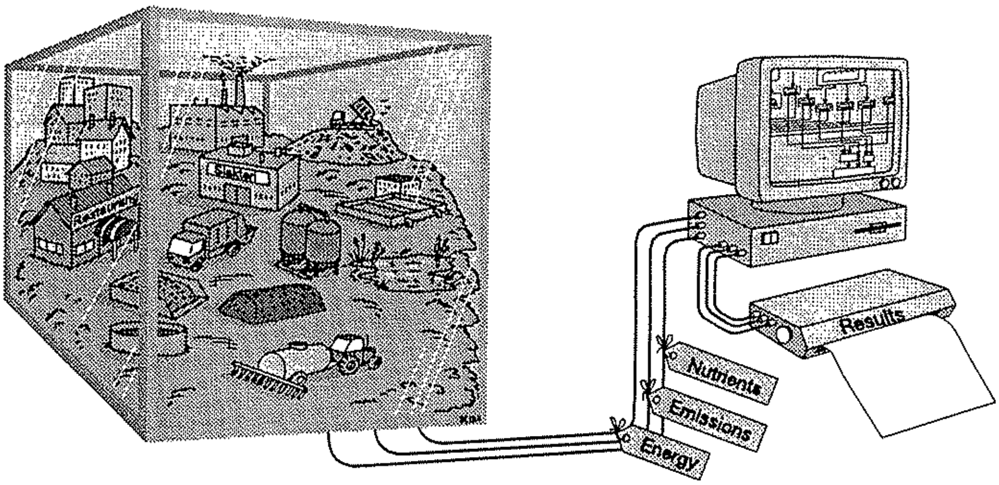

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ABSTRACT

A simulation model, called ORWARE (ORganic WAste REsearch model), has been developed for evaluation of handling alternatives for organic waste. The model deals with both source separated solid organic waste and liquid organic waste i.e. wastewater. Included are transport for collection, incineration, landfilling, anaerobic digestion, composting, transportation of residuals and spreading on arable land. The model is intended for simulation of handling scenarios for organic waste and calculates emissions to air, water, recirculation to arable land and energy turnover. The flows in the model are described by a variable vector of 43 substances, including e.g. plant nutrients, heavy metals and some organic priority pollutants. The construction of the models for anaerobic digestion, sewage plant, sewage system and spreading of residuals included in ORWARE, are described in detail.

The anaerobic digestion model is a continuous, single stage, mixed tank reactor (C.S.T.R.) operating under mesophilic conditions. The gas production is related to the retention time and the maximum degradation ratio and first order rate constant, for the organic components fat, protein and three classes of carbohydrates respectively. The combustion of the gas in a stationery engine is also included.

The sewage plant model includes mechanical, biological and chemical treatment of the wastewater, and anaerobic digestion and dewatering of the sewage sludge. The separation of sludge is based on the suspended solids and water separated in the respectively treatment processes with data primarily from the plant in Uppsala. Separation of the remaining substances included in the vector is principally modelled from assumptions of the substances to be attached to the suspended solids or soluble in water.

Sewage systems included are conventional systems and vacuum systems. The model deals with leakage and energy consumption. Alternatives in ORWARE are also urine separation and kitchen disposers for transporting and treating the solid organic waste in a sewage plant. These alternatives changes the substrate composition and water quantity sent to the sewage plant.

The model for spreading of residuals includes three types of spreaders, depending on the residues water content. It models energy consumption and emissions from the tractor.

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1. INTRODUCTION

Interest in urban/rural circulation systems of organic waste has increased, with focus on source separation and biological treatment such as composting and anaerobic digestion. Also new alternatives for handling of wastewater, increasing the possibilities for circulation of nutrients, are under development. The intention of the new handling methods is to enable plant nutrients in the organic waste fraction to be recirculated and to reduce the environmental impact of waste handling.

The handling of organic waste is complex with numerous processes and transportation activities involved. When introducing new systems it is therefore important to analyse all part of the system. Otherwise a reduction of the environmental impact in one part of the system may result in a larger increase in another part.

Different waste-handling systems for solid and liquid organic waste were studied in a project called "Systems analysis of Organic Waste" (Nybrant et al, 1996). The basic hypothesis in the project was that better treatment methods for organic waste than used today could be found. This concerns systems with low environmental impacts, high energy turnover and high re-use of nutrients. Therefore, a computer model called ORWARE (Organic Waste Research Model) was constructed to simulate the consequences of different handling scenarios.

The activities included in the ORWARE model are the collection of waste, waste treatment and final disposal of residuals. The residuals can be transported and spread on arable land or put on a landfill. Transportation can be done with garbage trucks, ordinary trucks, a sewage system, or a vacuum sewage system. The model calculates emissions to air and water, and the residues recycled to soil, and also the energy input and output. From the residues recycled to soil the amount of nutrients returned to soil can be calculated. The emissions from arable land after the spreading of residuals are not included in the model.

This report gives a short general description of the ORWARE model, and a detailed description of the sewage plant and anaerobic digestion sub-models, as well as the sewage system and spreading sub-models. Other sub-models in ORWARE are:

- Incineration (Mingarini, 1996)
- Landfilling (Mingarini, 1996)
- Composting (Sonesson, 1996)
- Transport (Sonesson, 1996)
- Transport distances for residues to arable land, (Sonesson, 1996)

The project "Systems Analysis of Organic Waste" was funded by the Swedish Waste Research Council (AFR) and was performed between 1993-1995. It was a collaboration project between the Swedish Institute of Agricultural Engineering, The Swedish University of Agricultural Sciences, The Royal Institute of Technology, and The Swedish Environmental Institute. The work is continuing in the new project "Modelling of municipal waste management systems".

2. MODELLING

The reasons for making a model can be:
- A real system does not exist for some of the studied processes,
- It would be too expensive, time-consuming and hazardous to conduct experiments on the studied system itself,
- The surroundings of the system can not be controlled when conducting experiments,
- The modelling work gives knowledge and understanding of the system,
- The model itself is a valuable pedagogic tool to convey knowledge about the system.

All descriptions and representations of reality are models. A model may be mental, verbal, physical or mathematical (Miser & Quade, 1985).

A mathematical model can be used predictively, for education, and for process control and design. However, a model is always a simplification of real-life and a compromise between accuracy, applicability and clarity. A model with high accuracy often become very complex with numerous parameters. This creates problems in getting accurate values of the parameters and the model will also be less generally applicable. When developing a model, it is therefore essential to keep the purpose of the model in mind. This governs the complexity of the model.

Type of model

The purpose of the project "Systems analysis of organic waste" was to study different handling systems of organic waste and their consequences for the environment, energy turnover and return of nutrients. A mathematical model approach was chosen. Mathematical models can be classified in different types.

- Dynamic or static
- Linear or non-linear

The ORWARE model is constructed as an static model. Incineration can be considered as a static process, where the process does not depend on what has been introduced before the time of study. However, anaerobic digestion, composting and landfilling are dynamic processes. Nonetheless, a dynamic model would not produce more information, since detailed figures of waste generation both in composition and quantity are only found as yearly averages. A dynamic model also becomes much more complex, needing more detailed knowledge about structure and additional data. Another difficulty with the treatment processes in a dynamic model would be the totally different time perspectives. The errors introduced by approximating the waste to be equally distributed over the year were also considered to be reasonably small in comparison with other uncertainties.

The processes in the ORWARE model are mainly described by linear relations, although some non-linear relations also appear, making the total model non-linear. The effect of this implies that the result of the model for two different substrates can not be added and considered to be valid for handling of the two substrates together.

Structure

An important part of the modelling is to find the right structure of the model with an optimal level of aggregation and details. It is not necessarily true that a model is better if it includes more details. The aim of the study is primarily to decide the structure and level of details.

The modelling work can be done as top-down or bottom-up. The top-down approach is starts with a rough description of the total system and then separates this and adds more details, until a relevant level of details is reached. If, instead, the knowledge of details in the system is known, they can be aggregated until they are structured to a whole model. This is the bottom-up technique.

In the construction of the ORWARE model, as in many other situations, a combination of the top-down and bottom-up approach was used when compiling the knowledge of the handling system for organic waste. The main part of the modelling work has been done separately for the different treatment processes. Therefore, an important aspect in structuring the model was to achieve the same level of detail in all the sub-models.

The entire model consists of a number of processes for transportation and treatment. These processes, in the same way, consist of a number of sub-processes. All processes are constructed within the same principles (Figure 1). The processed material flow is calculated from the flow of material to the process. Consumption of energy and resources is also related to the material flow into the process and also the energy output and emissions of air and water. However, in some sub-processes one or more of these flows can be zero.

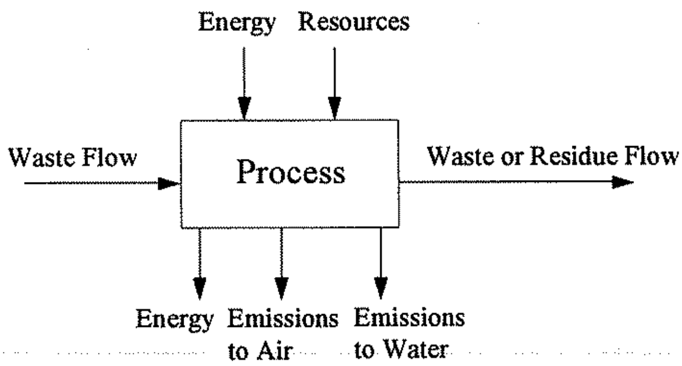

Figure 1. A general description of a process model.

The principle when relating the flows to the influent material will change in the model due to the complexity and to information on the structure and data. The principles can be divided in the following groups:

- **Mechanistic**. When the process is described by natural laws, as chemical formulas.
- **Empiric**. If the process is described from experiment studies, where statistic relations have been established between indata and results.
- **Measurements**. The process is modelled from reality or experimental measurements, but without any statistical evaluation.
- **Plausible assumptions.**

The last three groups are examples of black box modelling, where flows from the process are related to the flow into the process only from studies of the parameters without knowing the detailed background of natural laws.

System boundaries

At the beginning of the project "Systems analysis of organic waste" a conceptual model was established to clarify the system boundaries and what processes to include in the model. The inputs to the system are waste streams and energy, and the outputs are emissions, energy and residual products (Figure 2).

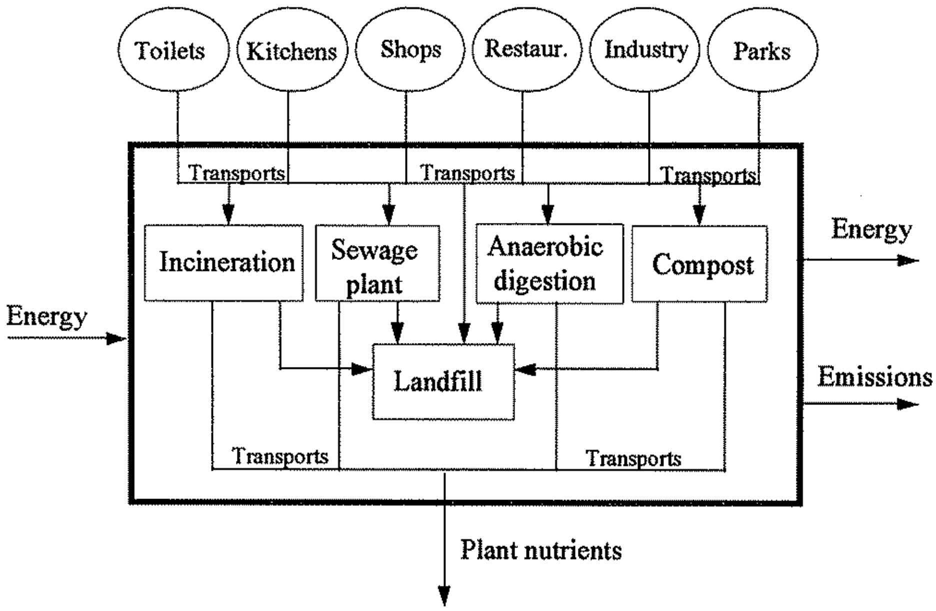

Figure 2. The conceptual model for the system for handling of organic waste.

The activities included in the model are: the collection and transportation of the waste fractions, treatment of waste, transportation of residuals to recycling or final disposals. In the case of, e.g. compost and sludge, this also includes spreading on farmland. The system boundary is then defined as the moment when the residual reaches the ground.

The model covers only the direct emissions from the waste handling system. The emissions from constructing the infrastructure, buildings and machines are not included in the model.

Energy flows are calculated in the model. For oil used in the system, emissions from combustion are included, but not emissions related to the production of oil. Furthermore, emissions involved with the production of heat and electricity from gas obtained is included in the model. However, no emissions is achieved when consuming heat and electricity in the model. In scenarios with net consumption of heat and electricity, this have to be produced from sources outside the system, and the emissions related to this activity are not included in the model.

The vector

The interface between all the processes is a vector of the same structure with 43 defined positions (Table 1). The vector is able to describe both solid liquid and gaseous flows in the model, i.e. both waste flows and emissions. However, the energy flow is handled separately in the model. Having the same vector for all flows makes it easy to add more sub-models and also to change flows of materials to different processes.

Table 1. The vectors used in the ORWARE model

No.	Substance	Remarks
1	C-tot	Total carbon
2	C-chsd	Carbon in slowly degradable organics, i.e. lignin
3	C-chfd	Carbon in rapidly degradable carbohydrates, i.e. sugars, starch
4	C-fat	Carbon in fat
5	C-protein	Carbon in protein
6	BOD_7	Biological oxygen demand during 7 days
7	VS	Volatile solids (DM - ashes)
8	DM	Dry matter
9	CO_2 -f	Carbon dioxide of fossil origin
10	CO_2 -b	Carbon dioxide of biological origin
11	CH_4	Methane
12	VOC	Volatile organic compounds, e.g. methane, solvents
13	CHX	Halogenated hydrocarbons
14	AOX	Adsorbable organic halogens
15	PAH	Polyaromatic hydrocarbons
16	CO	Carbon monoxide
17	Phenols	
18	PCB	Polychlorinated biphenyls
19	Dioxins	Measured as TCDD equivalents according to Eadon
20	O-tot	Total oxygen content, except oxygen as H_2O
21	H-tot	Total hydrogen content, except hydrogen as H_2O
22	H_2O	Water
23	N-tot	Total nitrogen
24	NH_3/NH_4^+ -N	Nitrogen in ammonia or ammonium
25	NO_X -N	Nitrogen in nitrogen oxides
26	NO_3^- -N	Nitrogen in nitrate
27	N_2O -N	Nitrogen in dinitrogen oxide
28	S-tot	Total sulphur
29	SO_X -S	Sulphur in sulphur oxides
30	P-tot	Total phosphorus
31	Cl-tot	Total chlorine
32	K	Potassium
33	Ca	Calcium
34	Pb	Lead
35	Cd	Cadmium
36	Hg	Mercury
37	Cu	Copper
38	Cr	Chromium
39	Ni	Nickel
40	Zn	Zinc
41	C-chmd	Carbon in moderately degrad. carbohyd., i.e. cellulose and hemicellulose
42	Particles/SS	Particles in gas and suspended solids in water
43	COD	Chemical oxygen demand

The selection of parameters to be included in the vector was made from the requirement that the parameters should meet at least one of the following criteria:

- be of importance for the environment,
- be of importance for the processes,
- have an economic value.

For the biological processes the degradability and the degradation rate depend on the quality of organic material. Thus, the organic fraction was characterised as protein, fat and three groups of carbohydrates. It is important to observe that these fractions are given as kilograms of carbon.

Computer implementation

The modelling is implemented on a computer with the program language MATLAB/Simulink (Maths Works Inc., 1993). There were several reasons for choosing this program. The program has a hierarchic structure making it possible to add more details in underlying levels without changing the main structure. The simulink interface is also pedagogic, making it both easy to program and easy to understand, and following the flows in the model. Furthermore, the MATLAB is a widespread calculation tool with possibilities of matrix operations. The program has possibilities for both static and dynamic modelling, ensuring flexibility for future development.

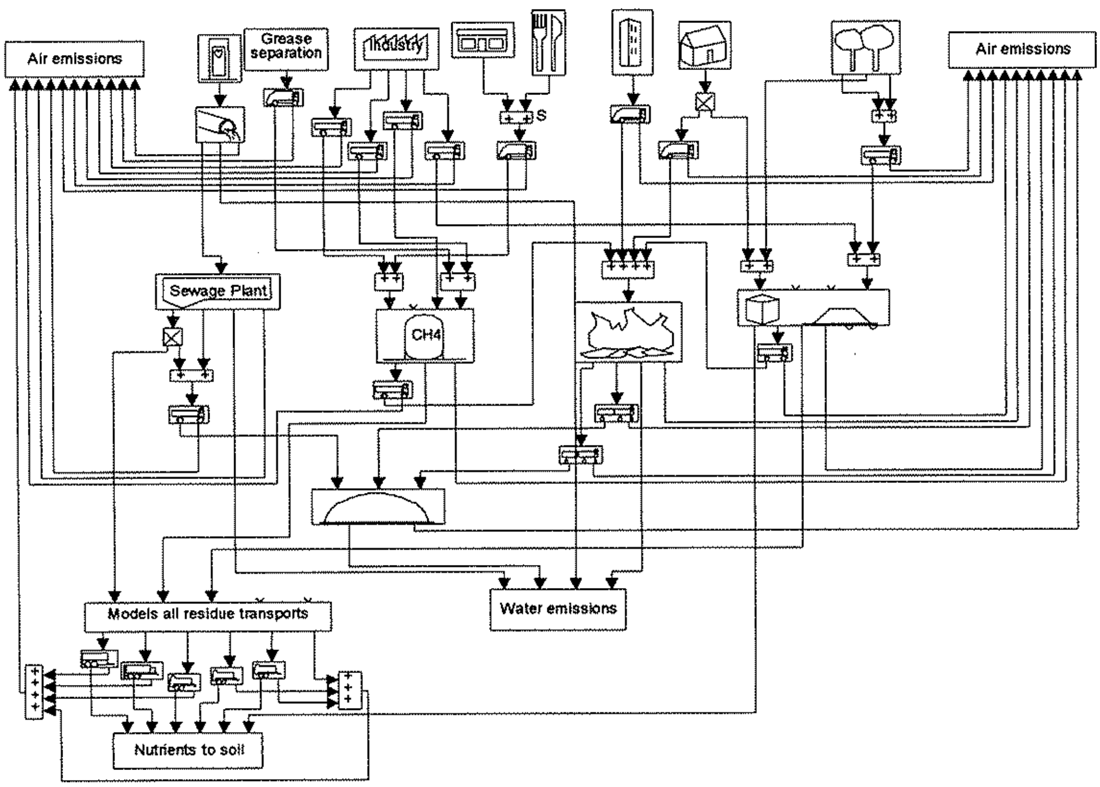

Figure 3. An example of a scenario for handling of organic waste with the ORWARE model.

Verification

When finishing the anaerobic model and sewage plant model, they were technically validated by constructing similar spreadsheet models in Excel. By this procedure some defects of the sub-models were detected. However, the sub-models become very complex and difficult to handle as spreadsheet models, making it impossible to test the entire model by this technique.

A sensitivity analysis is important when evaluating a model. This is done by varying the parameters and recognising how these changes influence the behaviour of the model, thereby identifying what parts of the model have the highest influences. However, it is also necessary to test for interaction variation, changing more than one factor in a time. An analysis where all parameters and combinations are tested will often result in a massive time-consuming evaluation. Therefore, the Monte Carlo simulation method is often used, where uncertain parameters are selected randomly (Miser & Quade, 1995). For linear models the analysis can be focused on parts of the model having the highest influence on the result.

The ORWARE model is largely linear. Therefore, the sensitivity analysis has been concentrated on calculations of emissions with major influences on the total result of both sub-model level and the entire model. Efforts have then been made to improve these parts of the model by introducing better data and a more detailed structure. An example is the emissions of SO_X, resulting in a high impact on acidification.

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3. ANAEROBIC DIGESTION

The purpose of the anaerobic digestion model in ORWARE is to predict emissions and energy flows from digestion of organic waste materials. Important parts are, therefore, the amount and composition of gas produced. This gas is combusted resulting in heat, electricity and emissions. The residual sludge is also of interest, both its content of nutrients and contamination, and its amount, which decides the work needed for transporting and spreading. Both pretreatment and storage has been included in the model.

Several different anaerobic digestion models are found in the literature. They can primarily be divided into two types, dynamic and static models. The dynamic models can be used for control purposes and to predict process failures, while static models are useful for process design applications. In the dynamic models, first order kinetics is often used, calculating the rate of substrate utilisations from the substrate concentration, rate constant, microbial concentration and saturation constant (Monod, 1950). These models assume that rates of substrate utilisation and product yield depend on the microbial growth rate. Further developments of these types of models have attempted to account for inhibition and solids solubilisation effects. An elaborate review of dynamic models are presented by Dunn et. al. (1994). These models are adopted for treatment defined substrates influent respectively. Preatreatment and dewatering processes are not included in these models.

An example of a static model is shown by two spreadsheet models in Lotus 1-2-3, for digestion of municipal solid waste and terrestrial biomass, respectively (Legrand et al., 1990; Legrand et al., 1988). Both models focus on energy and economy for an entire digestion system. A static anaerobic digestion model also calculating environmental effects is included in a "Life cycle inventory" model for integrated solid waste management (White et al., 1995).

However, no computer model which calculates the gas production from a mixed organic fraction or a fraction with unknown origin have been found. A model calculating gas production from the composition of the waste only, without knowing the origin, can be used for modelling digestion of a wide range of organic compounds and mixtures. Furthermore, the waste flows in the model do not then have to be kept separate.

In the anaerobic digestion plant modelled in ORWARE, the waste passes through different pretreatment processes such as metal separation, maceration and different levels of hygienisation. Thereafter, the material is diluted to an appropriate dry matter content. A heat exchanger is used to heat the material before it is introduced into the digester. The anaerobic digester is a continuous, single stage, mixed tank reactor (C.S.T.R.) operating at a mesophilic temperature. After digestion, the residue passes through the heat exchanger, reducing the microbial activity and transferring the heat to the influent substrate. Finally, the digested material is dewatered and stored in covered lagoons until the spreading season. The gas produced during digestion is used for production of electricity and heat in a stationary engine without any previous treatment.

The modelling of the anaerobic digestion precess is explained in the following sections (Figure 4).

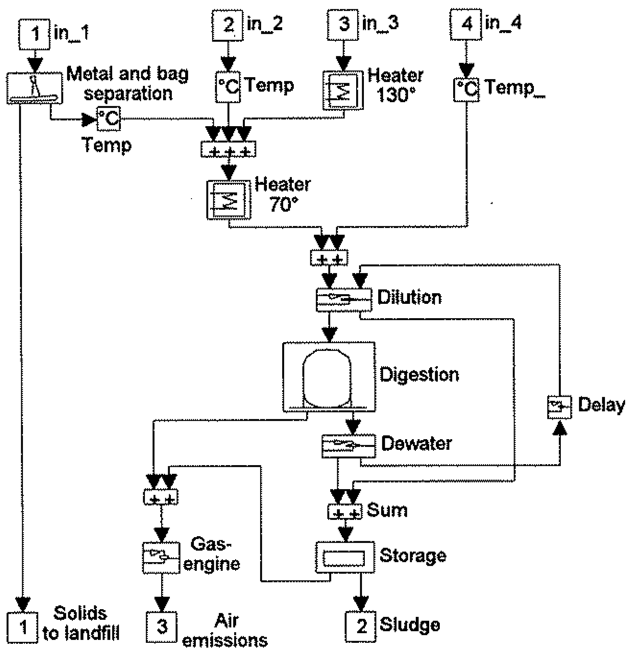

Figure 4. The anaerobic digestion model in ORWARE (Simulink).

Pretreatment

The requirement for pretreatment depends on the waste. Therefore, the anaerobic model has four separate entrances. The different pretreatments are maceration, two levels of hygienisation, and separation of metals and plastic bags. Maceration is needed for most of the waste in order to give microoganisms better accessibility to the material and to improve the possibilities to pump and mix the waste. Hygienisation of waste involves heating it to 70° or 130° C. Both maceration and hygienisation consume energy. The separation of metals and plastics also results in a loss of the organic waste which adheres to the metals and plastics.

Conventional slurry processes generally are done at a solids content of 3-10 % in the digester (Dunn, 1994). Thus before introducing solid waste into the digester, dilution is often necessary, which can be accomplished by addition of fresh water or circulation of liquid from the effluent. However, recirculation of liquid from the dewatering of the sludge does not reduce the levels of water-soluble components in the digester. Addition of fresh water reduces these levels, but also results in larger quantities of sludge from the digester to be stored, transported and spread. A highly diluted substrate leads to high heat consumption and investment costs for the digester. On the other hand, substrate with a high dry matter content causes problems with inhibitory levels of different compounds and physical problems with mixing and pumping the material. Thus, the dry matter content and the circulation ratio can be regulated in the model.

Gas production in the digestion model is not automatically reduced when inhibitory levels are reached in the digester. This requires that the concentration of cations has to be registered and the addition of water increased if inhibitory levels are reached for any substance. Significant inhibition of methanogenesis has been observed for the following concentrations of cations:

ammonium and magnesium 3 g/l, calcium and sodium 8 g/l, and potassium 12 g/l (Dunn et al., 1994).

Digestion

The total gas production in the model is related to the influent substrate and the retention time (HRT) in the digester. The formulas and figures in the following are used for calculation of biogas production on a yearly basis.

Without any factor limiting the biodegradation, the degradation rate will be proportional to the degradable carbon concentration in the digester. For a completely mixed reactor in batch digestion the degradation ratio (D) is well described by a first order kinetic model with the formula:

$D = D_0 * (1 - e^{-k*t})$

k = first-order rate constant
D_0 = maximum degraded ratio ($0<D_0<1$)
D = degradation ratio ($0<D<D_0$)

For digestion in a continuous single stage mixed tank reactor (C.S.T.R.) in steady state, the methane production can be related to the hydraulic retention time (R), by the first order kinetic model (Legrande et al., 1988):

$D = D_0 / (1 + 1/(k*R))$ R = hydraulic retention time [days]

However, different organic substances are decomposed at different rates. To be able to calculate the degradation ratio for a mixture of waste substrates, the degradation is calculated from degradation of its different organic compounds, i.e. fat, protein, rapidly degradable carbohydrates, moderately degradable carbohydrates and slowly degradable organics. The maximum degradation and rate-constants for these compounds are presented in Table 2. Furthermore, the total gas production is calculated from the quantity of organic compounds, the degradation ratio, and the proportion of methane in the biogas (m). As an example, the gas production from fat (B_{fat}) is calculated as follows:

$B_{fat} = C\text{-}fat*(m_{fat}*16/12+(1-m_{fat})*44/12) * D_{0fat}/(1+1/(k_{fat}*R))$

C-fat = carbon in fat in substrate [kg]
B_{fat} = biogas produced from fat [kg]

The slowly degradable organics (lignin) is not degraded in the digester and also diminishes the ability of the microorganisms to degrade moderately degradable carbohydrates (cellulose and hemicellulose) in the cell walls (Chandler et al, 1980).

Most of the organically bound nitrogen and sulphur is found in the proteins. Thus, in the model the organically bound nitrogen is released as ammonium of the same rate as the net degradation of protein in the digestion. Similarly, sulphur is emitted, primarily as dihydrogen sulphide in the gas, in relation to the net degradation of protein. However, the emission of dihydrogen sulphide is reduced if the waste contains ferrous compounds from e.g. precipitation chemicals, resulting in a considerable formation of FeS i.e. sulphides.

Table 2. Degradation of organic substances

Organic substances	Maximum degradation, D_0	Rate constant, k $days^{-1}$	Methane, m %
Organics, slow (chsd)	0	0.001[5]	50[4]
Carbohydrate, moderate	1.0 - 1.77*chsd[2]	0.18[1]	50[4]
Carbohydrate, rapid	1.0[2]	0.23[1]	50[4]
Protein	0.80[2,3]	0.13[1]	69[4]
Fat (after hygienisation)	0.95[3]	0.13[1]	78[4]

1) Estimated from Chynoweth et al, 1993
2) Chandler et al, 1980
3) Calculated from Edström et al, 1995
4) Mean value calculated from Roediger, 1967 and Burford et al., 1976
5) Assumed value, since zero is impossible to use in the formula

The organic pollutants are also affected by the anaerobic digestion process. Reduction of organic pollutants has been measured in a sewage sludge digester (Table 3). In the model, the entire reduction is assumed to be due to degradation and nothing emitted as gas.

Table 3. Reduction of organic pollutants in a mesophilic anaerobic digester with a hydraulic retention time of 30-40 days (Ring, 1993)

Substance	Reduction	Remark
PAH	12 %	Mean value of 5 substances
Phenols	13 %	Nonyl phenol
PCB	45 %	Mean value of 7 substances

Storage

The dewatering process separates the sludge leaving the digester into a solid and a liquid phase The quantity of each is calculated from the expected content of dry matter in the phase concerned. The digestion residue not circulated is stored in a solid and a liquid phase or mixed. In the separation module, the different compounds are thought to be either attached to the suspended solids or dissolved in the water, resulting in a separation proportional to the suspended solids and water, respectively (see the sewage plant model).

The residue is stored in lagoons. About 10 % of the ammonium is lost as ammonia during one season of storage (pers. comm. L. Svensson, 1994). With covered lagoons the emissions can be reduced to 1 % of the ammonium content.

Anaerobic digestion in Denmark indicates that between 5-10 % more methane gas can be extracted if gas from the storage lagoons can be collected (Lindboe et al., 1995). Assuming a figure of 10 % means that 5 % of the carbon in the residue is emitted as methane and carbon dioxide during storage. With covered storage the gas can be collected and mixed with the gas from the digester.

Energy

Energy for pumping and mixing of the materials requires approximately 2.5 % of produced energy (Krüger Bigadan, 1992). Another 2.5 % is assumed to be consumed for macerating and other pretreatment activities consuming electricity (calculated from Edström, 1995).

Most of the organic waste requires hygienisation to avoid spreading pathogens via the handling of the waste. Two levels of hygienisation are suitable, heating to 70° C and 130° C respectively. Infected material from a slaughterhouse needs 130° C and organic waste from households, restaurants, and most of the non-infected slaughter waste needs heating to 70° C for one hour. Some organic wastes do not require heating. The heating processes in the model only consume energy. They are not considered to influence the composition of the organic material or to produce any air emissions. The energy required is calculated with a mechanistic model from the temperature difference between incoming waste (10° C) and the hygienisation temperature, multiplied by the specific heat constant ($4.18*10^{-3}$ MJ/°C, kg) and material flow (dry matter + water). Another 20 % energy are added due to loss of heat.

Heat exchangers are included in the digestion plant. Different types of exchangers used in biogas plants have showed efficiencies between 40 % and 65 % (Prisum and Nørgaard, 1992). In the model, the heat exchanger is estimated to be able to reuse 50 % of the heat in the sludge when reducing the temperature from 37°C to 10°C. Heat from the hygienised material is calculated to be reused to 100 %, when reducing the temperature to 37°C before the material is introduced into the digester.

The heat requirement in the digester is calculated from a mechanistic approach. Heat consumption depends on the temperature of the digested material and the losses through the digester reactor during digestion. Depending on the proportion of the material hygienisated at 70 and 130° C and not hygienised, the material entering the digester needs to be heated or cooled. Losses of heat during digestion are calculated from the coating area of the digester, the size of which depends on the retention time and proportion between height and diameter (chosen to be 1.5).

Heat loss [MJ] = $(pi*(h*1.5)^2*2/4 + pi*h*1.5*h)*k*(37°-10°)*24*365*3.6$
where the equation (dry matter+water) $*R/(1000*365) = pi*(h*1.5)^2*h/4$
gives the value of h, and $k= 0.15$ W/m^2,°C , R = hydraulic retention time.

The gas is used in a stationary engine without any further purification. The energy produced by the engine is calculated from the energy content in the methane gas. Stationary engines produce about 30 % electricity and 60 % heat, the remainder is lost.

Table 4. Emissions from a stationary Jenbacher engine powered by biogas fuel and producing electricity and heat

Emission	g/MJ methane gas	Source
CH_4	0,10	from Sundqvist (1994)
VOC	0,16	from Ekelund (1989) (incl. CH_4)
CO	0,25	from Ekelund (1989)
NO_x	0,20	from Ekelund (1989)
CO_2	85	calculated from ca 65 % methane
SO_2	0,15	calculated from 2300 ppm H_2S

Validity range

The model is largely of general applicability for digestion in a continuous single stage mixed tank reactor (C.S.T.R.) operating at mesophilic conditions. The model is constructed for treating a wide range of organic materials, since degradation is related to organic components, protein, fat and carbohydrates. However, the model is not valid for materials that are highly diluted or concentrated, since it can not account for inhibition and solids solubilisation effects.

Chynoweth et al. (1993) attempted to find correlations between the extent of conversion (D_0) and rate (k) and the contents of cellulose, hemicellulose, lignin. They only succeeded for the extent of conversion and lignin content. There appears also to be a correlation between the rate of conversion (k) and the lignin content.

A verification of the model has primarily been done by simulating digestion of several organic materials with different retention times and comparing the gas production with figures found in the literature (Table 5). However, it has not been possible to find the organic composition of the substrates used in the literature data of gas production. The calculation method used in the model seems to correspond fairly well with the literature data. Also other figures, such as the degradation of organic nitrogen to ammonia and the concentration of hydrogen sulphide in the gas, have been compared with the literature and showed good correspondence.

Table 5. Figures of gas production achieved from simulations of the anaerobic digestion model. The organic composition is obtained from Sonesson & Jönsson (1996)

		Source separated household waste	Source separated waste from restaurants	Manure*	Slaughterhouse waste
Content					
Protein	% of DM	13	13	8.8	50
Fat	% of DM	18	24	0.7	37
Chfd	% of DM	22	19	0	2.7
Chmd	% of DM	23	20	57	0
Chsd	% of DM	4.4	4.0	8.0	0
TS	%	35	30	16	30
Gas production					
HRT=10	l CH_4/kg VS	210	190	155	160
HRT=15	l CH_4/kg VS	330	360	210	480
HRT=20	l CH_4/kg VS	360	395	230	520
HRT=30	l CH_4/kg VS	390	430	250	570
Gas composition	% CH_4	61	63	55	72

* Ca 50 % manure from pigs and 50 % from cattles.

Literature figures:
Source-separated municipal solid waste: 384-399 l CH_4/kg VS, with HRT=14-25 days and 61-63 % CH_4 (Mata-Alvarez et al., 1990).
Source-separated municipal solid waste: 540 l CH_4/kg VS, with HRT=50 days and 60 % CH_4 (Cecchi et al., 1990).
Pig solid manure : 200 l CH_4/kg VS, with HRT=22 days and 63 % CH_4 (Roustan et al., 1984).
Cattle solid manure : 160 l CH_4/kg VS, with HRT=26 days and 64 % CH_4 (Roustan et al., 1984).

Future development

A valuable development of the anaerobic digestion model would be to extend it to also include digestion at 55 °C. Adaptation of the model to digestion at thermophilic temperature would require a change of parameters, higher degradation rate (k) and also probably a higher maximum degradation ratio (D_0). The share of the organic pollution degraded and the energy balance will also be affected. With other digestion methods, such as plugflow or two phase digestion, a change in the model structure is also necessary. Plants with other configurations for e.g. pretreatment would primarily influence energy consumption.

The content of sulphur in the gas results in sulphur oxides when burning the gas. This sulphur oxide is one of the most serious environment impacts of the anaerobic digestion. An automatic reduction of sulphur content in the gas in relation to ferrous compounds in the digested material would, therefore, be an important improvement of the model in the future.

Emissions of NO_X from the combustion of gas in a stationary engine have resulted in high environmental impact. Options available when evaluating an anaerobic digestion scenario would be platina catalysts connected to the exhausted gas, reducing the emissions by 80 %. Another interesting alternative would be to use the gas as vehicle fuel.

It would also be desirable if the model warned when inhibitory levels of any compounds were reached. Data is not available for an automatic adjustment of the gas yield in relation to inhibitory levels. However, another probable development of the model would be to adjust the gas production in relation to pretreatment. The maceration processes, influence accessibility, and heating processes primarily influence the accessibility of fat.

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4. SEWAGE PLANT

The intention of the sewage plant model in ORWARE is primarily to calculate the part of influent emitted to the recipient or as sludge, and the gas production from digestion of sludge.

Models found in the literature are focused on the activated sludge process. One model, TOXCHEM, has been tested at the Swedish Environmental Protection Agency (Hellström & Rennerfelt, 1993). Mechanisms considered in the program are volatility, degradation and adsorption to suspended particles. Also other commercial models have been found, such as tools for plant design and evaluation (Science Traveller International, 1994). However, the models found do not cover the entire area of interest for this study, such as pretreatment and the sludge treatment, and neither do they include all the substances of interest. They are also more detailed, resulting in a lot of data needed for each plant studied.

The sewage plant model in ORWARE does not consider basin volumes or sludge retention times in the plant since it does not have the intention to give dimensioning criteria but to be a model for environmental impact calculations. The model is divided into pre-treatment with screen and sand separation, followed by three main treatment processes: presedimentation, biological treatment and chemical purification (Figure 5). The sludges separated in these three stages are digested and dewatered to a final sewage sludge product. This is the most commonly found design of larger sewage plants in Sweden.

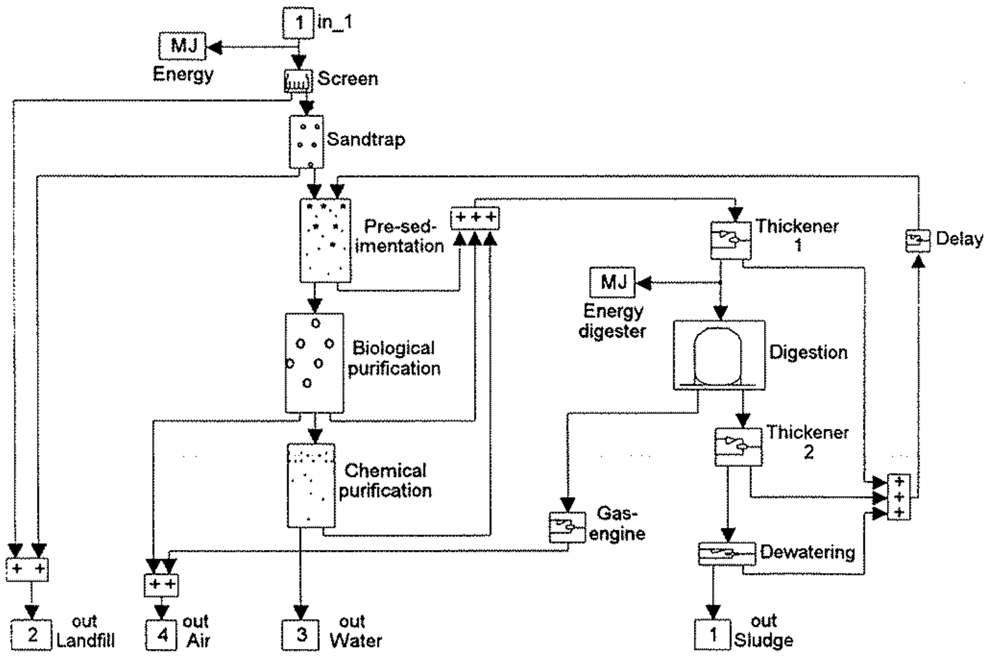

Figure 5. The Sewage plant model included in ORWARE simulation model..

The formation of suspended solids from chemical phosphorus precipitation, and also the activated sludge and nitrification/denitrification processes are primarily mechanistic models from chemical formulas. The other parts of the sewage plant model are for the major substances (i.e. SS, DM, VS, N, P, heavy metals) modelled from measurements, while some of the remaining substances have been modelled from plausible assumptions. Some generalisations have then been made. When separating a solid fraction from a liquid, e.g. in the screen, the substances are considered to be soluble in the liquid or attached to suspended solids. This implies that the compounds are separated in relation to the amount of water or suspended solids, respectively.

Table 6. Substances assumed to be soluble in water and/or attached to particles

Particles	Water
All organic compounds	NH_4^+
N-org	NO_3^-
S-tot	Cl
P-tot	K*
Ca*	
Heavy metals *	

* In some situations calculated separately (neither only water-soluble nor only attached to particles).

Pre-treatment

Large contaminants are separated as the wastewater passes through a screen. The amount of separation depends on the size of the screen openings. In the model, separation of sludge is calculated as a ratio of the suspended solids (SS) in the waste water introduced to the screen and with a specific content of dry matter (DM) and volatile solids (VS). These parameters are specific and depend on the screen size, the sewage system and the actual wastewater. Figures of separated quantities of SS, DM and VS are therefore taken from the actual plant studied. Separation of all other compounds are calculated to be separated in relation to the separation of SS, DM, VS or water. An example of data from the sewage plant in Uppsala is shown in Table 7.

Table 7. Separation of sludge in the pre-treatment of the sewage plant in Uppsala (from Uppsala reningsverk, 1992 and personal comm. Swedling, 1994)

	Sludge separated ton/year	Dry matter in sludge	Volatile solids of the dry matter	Part of suspended solids separated (calculated)
Screen	530	16 %	60 %	1.7 %
Sandtrap	110	30 %	26 %	0.3 %

The sandtrap (gritting) has the purpose of separating sand and other heavy unorganic materials through sedimentation in an aerated basin. Sand particles larger than 0.15 mm in diameter have to be removed, which results in separation of between 5 and 20 dm^3 sand/person and year (Rennerfelt, 1991). This part of the model works as the screen with statements of the part of suspended solids separated, together with figures of DM and VS in the sludge. These figures are also taken from the actual studied plant. The influence of aeration on the volatile solids in the wastewater is not taken into account, but is included in the activated sludge part of the sewage plant model. The dewatered sludges from both the screen and the sandtrap are transported to deposition.

Presedimentation

In the presedimentation process, sludge is separated in relation to the suspended solids in the influent water. Sludge quantity is also determined from the dry matter content in the sludge obtained. The modelling of the remaining substances is related to the separation of suspended solids and/or water. The separation module has the same construction for sludge separation in all three treatment stages. However, the share of suspended solids separated and the DM content in sludge differ. Figures used in the model are presented in Table 8.

The share of suspended solids separated depends on the type of precipitation. If pre-precipitation is used 85 % of the suspended solids in the influent is separated and with post-precipitation 65 % (pers. comm. Rennerfelt, 1994). Morse (1993) presents a figure of 60 % SS removal (range 50-70%) if no chemicals have been added. The model calculates with pre-precipitation with $FeCl_3$. Formation of suspended solids due to precipitation is assumed to be totally done before the presedimentation. The amounts of suspended solids produced are calculated from the chemical formula (see phosphorus removal).

Table 8. Suspended solids separated in the sedimentation stages and dry matter in the sludge formed (pers. comm. Rennerfelt, 1994; Appendix 1)

	Presedimentation	Separation in biological stage	Separation in chemical stage
SS removal, % of influent (R_{SS})	85 %	65 %	75 %
DM content in sludge (DM_{sludge})	2.5 %	1 %	0.7 %

The separation of volatile solids is related to the SS and the ratio volatile solids of suspended solids (VSofSS). The ratio VS of SS is about 70 % in the influent wastewater (Rennerfelt, 1991. Morse, 1993). Due to precipitation and the activated sluge, this figure changes throughout the plant. Therefore, VSofSS is recalculated in the presedimentation and activated sludge stages in relation to the precipitation and microbial solids formed in the model. The volatile solids are assumed to have the same organic composition as the influent wastewater.

Calculation of separation of SS, H_2O, VS and DM to sludge is given below as an example:

$SS_{sludge}= R_{SS}*SS_{in}$
$H_2O_{sludge}=(1-DM_{sludge})*SS_{sludge}/DM_{sludge}$
$VS_{sludge}= SS_{sludge}*VSofSS_{in}$
Where R_{SS} and DM_{sludge} can be found in Table 8.

The total carbon separated is calculated from the VS and carbon content of the VS in waste water. Furthermore BOD_7 and COD are related to the total carbon with the following approximation (Sundqvist, 1993):
$COD= 3*C\text{-tot}$
$BOD_7= 1.2*C\text{-tot}$

Heavy metals separated in the sludges from all the three treatment stages have been measured and accounted for in Table 9 (Rennerfelt, 1992). The other substances are related to the separation of suspended solids or water, depending on whether they can be considered as mainly water soluble or attached to particles (Table 9). The potassium and calcium are, however, adjusted to get a more correct value of the content in the final sludge.

Table 9. Removal of heavy metals in the different treatment processes in relation to the total influent quantity (Rennerfelt, 1992). In parenthesis are the corresponding figures but related to the quantity of metals in the influent into the different treatment stages respectively.

Heavy metals	Presed. sludge %	Biosludge %	Chemsludge %	Total reduction %
Cd	44	20 (26)	4 (11)	68
Pb	40	24 (40)	18 (50)	82
Cu	41	31 (52)	19 (68)	91
Cr	43	29 (51)	12 (43)	84
Ni	-26 (0)	29 (23)	-10 (0)	0
Zn	54	7 (15)	14 (36)	75

Biological treatment

The biological treatment is an activated sludge process, with an aerated zone followed by a sedimentation step. Biological treatment has the main purpose of transferring soluble substances to suspended solids by growth of aerobic microorganisms.

The activated sludge model starts with the achieved reduction of biological oxygen demand (BOD_7) by ca 94 % (calculated from a total reduction of 97 % in the plant, Uppsala Avloppsreningsverk, 1993). During cell growth, oxygen are consumed through assimilation (55 %) and through oxidation of carbon to carbon dioxide (45 %). The assimilation of BOD_7 results in about 0.75 kg SS/kg BOD_7 which can vary in a range between 0.4 and 1.1 (Mores, 1993; Rennerfelt, 1991) depending on the load. The oxidation and assimilation of volatile solids are estimated to be equally divided among the different organic compounds.

The aeration necessary is calculated from the BOD_7 removal and oxygen ratio in air. However, the actual aeration intensity is approximately 30 % higher than the theoretical value (Rennerfelt, 1991). The aeration also results in emission of ammonia. In the model these emissions are related to the ammonia concentration in water, air volume, temperature and pH using a mechanistic approach (Svensson, 1994), where the ammonium in water is assumed to be in equilibrium with ammonia in the aerated air and with a water temperature of 15 °C and pH 7.7.

There are also emissions emitted of N_2O. Emissions of N_2O in a range of 0.03-0.12 % of the total nitrogen influent have been registered in a number Swedish sewage plants enlarged for nitrogen removal (Björlenius, 1993). The higher values are from older plants with low aeration capacity. A figure of 0.05 % is used in the model.

The separation of sludge from the biological treatment is calculated in the same way as the sludge separated in the presedimentation. However, the reduction of suspended solids is lower (ca 65 %) and the content of solids in the sludge is lower (1 %) in comparison with the primary sludge (Table 8).

Nitrogen removal

To decrease the eutrophication, a 50 % reduction of nitrogen is set up as a goal in Sweden for sewage plants in coastal areas. This is often achieved by transferring the ammonia to nitrogen gas, through a combination of the processes nitrification and denitrification.

Nitrification $NH_4^+ + 2O_2$ ---> $NO_3^- + 2H^+ + H_2O$
Denitrification $5/4C + 1/2H_2O + NO_3^-$ ---> $1/2N_2 + OH^- + 5/4CO_2$ (Rennerfelt, 1991)

The nitrogen removal can be done as pre-denitrification or post-denitrification. Pre-denitrification is the most common method for large sewage plants in Sweden. In pre-denitrification the anoxic denitrification step is first, followed by nitrification, with a circulation of nitrate-rich water to the denitrification step. The removal of nitrogen in the model is a pre-denitrification process with a reduction of nitrogen to nitrogen gas at 30 % which, together with the nitrogen in sludge, gives a total reduction of 50 % of the nitrogen in the effluent. In sewage plants without anaerobic digestion of sludge about 30 % of the nitrogen will end up in the sludge. Furthermore, the remaining ammonia is to 90 % converted to nitrate. The emission of N_2O increases in relation to an ordinary activated sludge treatment due to high nitrate levels and is around 0.15 % of the influent nitrogen (Björlenius, 1993).

The calculation of carbon dioxide emissions and BOD_7 is based on the chemical formula above. The remaining BOD_7 not consumed for the nitrification is used for cell substance assimilation and carbon dioxide respiration to an extent of 55 % in a similar way as in the biological treatment without nitrogen removal. Emission of ammonia to air is calculated from the total need of air for nitrification and BOD_7 removal.

Phosphorus removal

The phosphorus is reduced by chemical precipitation using $FeCl_3$. A mechanistic approach with the chemical formula described below is used for this process model. With the figure of ca 97 % removal of phosphorus, the amount of sludge can be calculated.

$2Fe^{3+} + 3OH^- + HPO_4^{2-}$ ---> $FePO_4 + Fe(OH)_3 + H^+$ (Rennerfelt, 1991)

The precipitation chemical has to be added in excess. An investigation of 20 Swedish sewage plants, showed a relation between the phosphorus content in the treated wastewater and the amount of added chemical. It also pointed out that the degree of removal depended more on the amount of precipitation chemical than on the precipitation method (Rennerfelt, 1991). Ca 75 % of the plants were in an interval of :

$y = 1,1(+/-0,2) - 0,56 * x$ [mg P/dm^3] x = mol metal / mol P in influent

Therefore, the amount of precipitation chemicals is calculated from the phosphorus removal obtained. The amount of chemicals is important since it contains heavy metals (Table 10).

The amount of chemicals used can also often be found in the environment report for the sewage plant. This figure can be used as comparison.

Table 10. *Heavy metals in the precipitation chemical $FeCl_3$(PIX-111 with 177 g Fe/kg, Uppsala Sewage plant, 1993)*

Heavy metals	mg/kg
Cd	0.01
Hg	0.013
Pb	0.7
Cu	3.1
Cr	6.9
Ni	5.3
Zn	12

The share of suspended solids separated in the chemical sedimentation step is approximately 0.75 and the sludge has a content of total solids of 0.7 % (Rennerfelt, 1991). The calculation of separation of other compounds is similar to the separation of sludge in the presedimentation.

Sludge treatment

The sludges from presedimentation, biological and chemical treatment are often digested and dewatered before storage and final disposal. Sludge treatment in the Uppsala sewage plant starts with a thickener, increasing the content of dry matter to 4 %. Then the sludge is digested involving degradation of around half of the dry matter content. Thereafter follows a second thickener increasing the suspended solids to 3.5 %, and finally the sludge is dewatered to a dry matter content of ca 25 %.

The liquid phase from the thickener and dewatering processes is returned to the primary sedimentation for further purification. The separation of a liquid and a solid phase is calculated from the suspended solids and water, as in the previously sedimentation processes. Modelling data for separation of suspended solids and water are found from measurements in the sewage plant in Uppsala (pers. comm. Swedling, 1993).

The anaerobic digestion of sewage sludge works in the same way as the digester in the anaerobic digestion plant. However, the hydraulic retention time is 15 days and the content of dihydrogen sulphide has to be reduced by 1/1500 due to formation of sulphide compounds from precipitation chemicals.

Energy consumption

Balmér and Mattsson (1993) present the total electricity consumption from 27 sewage plants in Sweden. With a regression analysis the total electricity consumption is related to the size of the plant in the number of thousands of person-equivalents connected (Appendix 1).

Total electricity consumption = $482,4*(P)^{-0.2957}$ MJ/pe, year ($R^2 = 0.77$)

P=Number of person equivalents / 1000, served by the plant

This does not include the pumping of wastewater to the sewage plant. The electricity consumption for other use than aeration is plausibly assumed to be 55 % of the total consumption calculated above, since the electricity use for aeration is considered to be a little less than half of the total (Balmér and Mattsson, 1993).

The model calculates the aeration electricity separately and related to the BOD_7 and N content. An energy consumption for aeration in the biological treatment of 4,0 MJ/kg BOD_7 removed is used in the model. In the literature, the energy consumptions reported are 4.0 (Morse et al., 1993), 3.6 (Kärrman, 1996) and 1.4-12.6 (Balmér & Mattson) MJ/BOD_7 removed. Electricity for aeration at the nitrogen removal is also calculated as 4.0 MJ/kg O_2 needed, giving a figure of 18 MJ/kg reduced N (The chemical formula result in 4.6 O_2/kgN*4.0 MJ/kg BOD_7), while Kärrman (1990) reports a figure of 14 MJ/kg N reduced.

A main energy-consuming process in the sewage plant is the heating of the reactor for anaerobic digestion of sewage sludge. This is often performed by using the produced gas. Approximately 40 % of the gas is used for heating (Swedling, 1995 and Kärrman, 1995). This results in a heat consumption of around 100 MJ/m^3 digested material (4 % DM) in the Uppsala sewage plant. This figure is used in the model, since the energy needed for heating the digester primarily would be related to the volume of digested material rather than to the gas produced.

Validity range

The function of the activated sludge process depends on a wide range of biological processes. The processes depend on, e.g. retention time, recirculation of sludge and concentrations of substances in the basins. However, these conditions not are included, making it possible to adapt the model primarily using the environmental report from the studied sewage plant. However, this makes the model only valid for calculation of normal operational conditions and, additionally, it is not valid for small sewage plants since they run under fairly different operating conditions.

Separation of urine in the toilet results in a large reduction of the nitrogen and phosphorus contents in the wastewater sent to the sewage plant. How this influences the plant operation has not been evaluated, since data from sewage plants operating under these conditions have not been found. The model's validity for such a situation can therefore not be decided.

If all the wastewater from toilets is separated, the remaining wastewater becomes very diluted. The content of volatile solids will then probably become too low for a normal operating sewage plant. The lower amount of flush water in the toilet does not influence the total wastewater dramatically since most of the water originates from bathwater, washing water and wash-up water.

Future developments

The calculations of emissions in the sewage plant are primarily done through separation of a proportion of the incoming water to sludge, which means that contaminations in the effluent wastewater are proportional to the influent wastewater. However, in practice the phosphorus in the effluent is reduced to a specific concentration due to regulations. Therefore the reduction of phosphorus in the effluent would be changed to be primarily related to the treated water quantity rather than to the amount of phosphorus in the influent.

Other treatment alternatives for sewage sludge would also be of interest to include in the model. In addition, an adaptation of the model to small sewage plants would be useful when using the ORWARE model in rural areas.

At present, electricity consumption is divided into consumption for aeration and consumption for other purposes. Relating electricity consumption for other use than aeration to activities such as dewatering and buildings, would probably increase the precision of the model.

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5. SEWAGE SYSTEMS

The sewage system transports the wastewater to the sewage processing plant. Different sewage systems can be included in the ORWARE model. With a vacuum system the water needed for flushing can be reduced. This is necessary if, e.g. the wastewater fraction from toilets is to be treated separately in an anaerobic digestion plant. However, the vacuum system results in a higher energy consumption. With vacuum systems in combination with urine separated toilets, the water for flushing can be further reduced. Separate treatment of urine in a conventional system will result in a high recirculation of nitrogen to farmland if the urine fraction is stored, transported and spread in a proper way.

With disposers in the household, the source-separated organic fraction can transported by the sewage system and treated in the sewage plant.

Conventional sewage systems

In Sweden, the most of the wastewater from households and industries is transported and treated separately from the run-off water. In some cases, however, drainage from houses are connected to the wastewater.

However, large quantities of water leak into the sewage system. These quantities can vary from 10 to 100 % of the wastewater production. The leakage varies, depending on weather and ground conditions and also on the conditions of the sewage system. Therefore, this parameter has to be adjusted to conditions in the studied city. When calculating leakage water volumes in plants for new sewage systems, a figure of 0.03-0.05 l/s, ha is used (Kapilashrami, 1990) which, in the case of Uppsala, gives a leakage into the system of around 30 %.

The energy consumption from transportation of wastewater differs widely between different cities due to ground conditions. However, the total electricity consumption at the pump stations in Uppsala gives a figure of around 0.8 MJ/m^3 waste water, which is used in the model (Appendix 2). Kärrman (1995) reports a figure of 0.4 MJ/m^3 wastewater without referring to any specific city.

Vacuum systems

The vacuum system model is constructed for transportation of wastewater from toilets. With a separate vacuum system for the toilets it will be possible to reduce the water consumption from six to almost one litre per flushing. The system is planned to be constructed with separate vacuum systems for smaller areas of up to 100 households collecting the wastewater at a pump station for further transportation under pressure to the treatment plant. Since the pipes have to be air- and water-tight, no leakage is expected.

The model assumes an energy consumption of 110 MJ/m^3 for the vacuum system and an additional 0.8 MJ/m^3 for the pumping of water from a transfer station to the treatment plant. These figures originate from a vacuum system in Bälinge built in 1970. Bälinge village near Uppsala has one single vacuum system (0.8 bar) serving around 2000 persons. This vacuum system has an electricity consumption of 520 MJ/person, year or 110 MJ/ m^3 (pers. comm. Östling, 1994. Appendix 2). The energy consumption of this system is probably rather high compared with a system built today due to the size and age of the sewage system, resulting in less efficient pumps and air leakage. Other figures in the literature suggest an energy requirement for a vacuum system of 480 kWh/person, year, which is commented as rather high, and new systems are under development with much lower energy consumption (Malmqvist et al., 1995).

However, by using the figure of 110 MJ/m^3 we get a total energy consumption of half that of the Bälinge system when caclulating with 1 liter/flushing due to lower water consumption. The energy consumption of 0.8 MJ/m^3 for transportation under pressure is taken from a conventional system and therefore is probably too low.

Urine Separation

Separate handling of urine involves separation toilets, storage tanks for urine and transportation to farmland and, finally, spreading of the urine.

The urine-separating toilets having a water consumption of about 1 dl per flushing. The reduction of water in the remaining wastewater fraction from households, therefore, is 6 litres per flushing in a conventional toilet and 1 litre for a vacuum toilet. No energy consumption is assumed to arise due to the urine separation, except for transportation and spreading of the urine which is accounted for by the respective ORWARE models.

Disposers

An introduction of disposers in the kitchens makes it possible to transport organic household waste within the sewage system. A study of disposers was made in Staffanstorp in Sweden (Nilsson, 1990). In that study the garbage-disposer required an additional water consumption of 3.4 l/person and day and an energy consumption of 3.7 MJ/person and year (Appendix 2).

When the disposer is used in connection with a vacuum sewage system the intention is to reduce water consumption by an estimated 25 %.

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6. SPREADING OF RESIDUALS

This model calculates the energy consumption and emissions from the spreading of residuals on the field. The transportation of material to the field is not included since it is included in the transport block.

Type of spreaders

Three different spreaders are included in the model: One for liquid products such as sludge from the anaerobic digestion with a dry matter of up to 12 %. Another for residuals with a higher dry matter content such as the sewage sludge with about 25 % DM, and a third for solid manure, e.g. suitable for the compost fraction.

Table 11. Types of spreaders used in the model, normal spreading loads, working capacities and energy consumption (pers. comm. Oostra, 1993)

Type of spreader	h/ha x l/h x MJ/l	MJ/ha
Spreader for liquid manure	0.35 x 35.8 x 35.4	444
Spreader for semi-liquid manure	1.35 x 13.1 x 35.4	626
Spreader for solid manure	0.35 x 13.1 x 35.4	162

Emissions from spreading

The emissions from spreading are taken from an investigation of about 25 diesel engines running in the terrain (Egebäck et al., 1991). This test measured the emissions in relation to the energy on the driving wheel. The emissions are then calculated in relation to the energy in the fuel with an energy efficiency of 34 % (Appendix 3). Emissions not found in these tests are taken from the transport model (Table 12).

Table 12. Emissions from a tractor (with an engine over 200 kW) in relation to the energy in the diesel fuel, calculated with an energy efficiency of 34 %

Compound	Emissions g/MJ	Figures from:
C-tot	20.3	ordinary trucks transport model (Sonesson, 1996)
CO_2	74	ordinary trucks transport model (Sonesson, 1996)
CO	0.333	Egebäck et al, 1991
CH_4	0.001	ordinary trucks transport model (Sonesson, 1996)
VOC	0.120	Egebäck et al, 1991
PAH	$2.5*10^{-6}$	ordinary trucks transport model (Sonesson, 1996)
N-NO_X	0.408	Egebäck et al., 1991
N-N_2O	0.0026	ordinary trucks transport model (Sonesson, 1996)
S-SO_X	0.093	diesel of environmental class (EC) 1 (Sonesson, 1996)
Particles	$13*10^{-6}$	ordinary trucks transport model (Sonesson, 1996).

Structure of the model

The model calculates the energy consumption and emissions from the weight of residuals (kg/year), spreading dose (kg/ha) and energy consumption (MJ/ha).

The spreading area needed is determined from the contents of phosphorus or nitrogen in the products. The maximum dosage is presumed to be 90 kg nitrogen and 15 kg phosphorus per year and ha. However, the phosphorus can be spread with a five-year dose at one time. If the relation between nitrogen and phosphorus is over 1.2 (90/75), the nitrogen dosage of 90 kg N/ha will determine the amount spread per ha and if it is lower the phosphorus yield of 75 kg/ha will determine the amount per ha.

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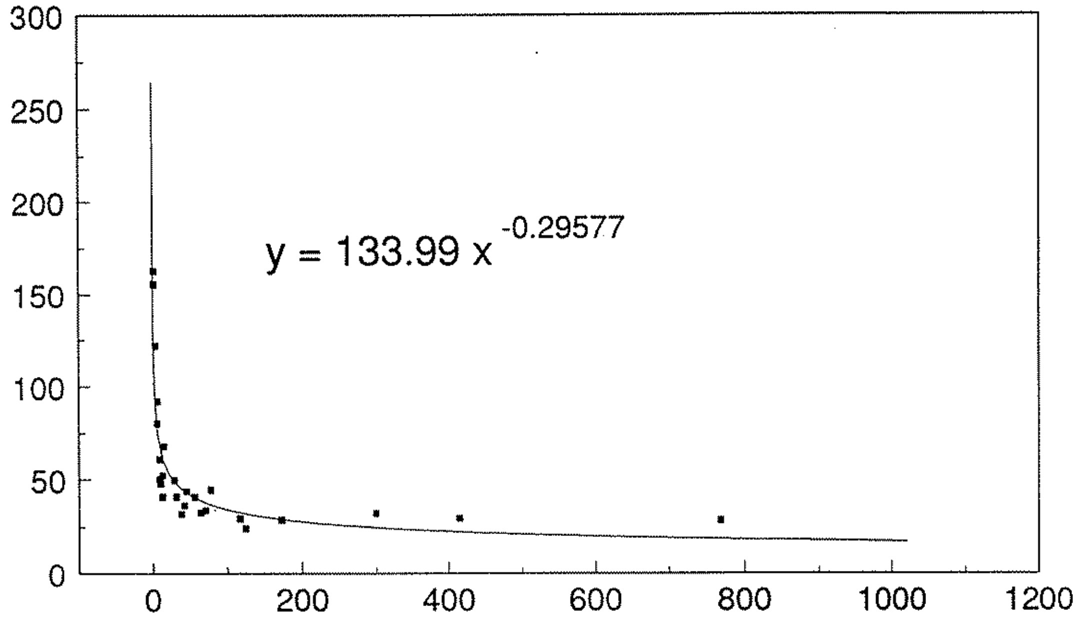
Appendix 1

Electricity consumption in sewage plants

Balmér and Mattsson (1993) present the total electricity consumption from 27 sewage plants in Sweden. With a regression analysis the total electricity consumption is related to the size of the plant in the number of thousands of person-equivalents connected.



y = kWh / pe, year
x = Number of person equivalents / 1000, served by the plant.
$R^2 = 0.77$

Separation of sludge in sewage plants

Table 13. Separation of sludge in a sewage plant (Rennerfelt, 1991)

Process		Sludge amount g/m³ wastewater	TS %	Volume l/m³	Chemical dose
Presedimentation		120	2-3	5	
Biological bed		50	0.8-1.2	5	
Activated sludge		70	0.8-1.2	7	
Chemical treatment	Fe	70	0.6-0.8	10	25 g Fe/m³
	Al	50	0.5-0.7	8	150 g AVR/m³
	Ca	600	1.5-2.5	30	400 g lime/m³

Morse presents slightly higher figures of dry matter content in the different sludges. For primary sludge the concentration may be 2-8 % DM with a typical figure of 4 %, and the secondary sludge concentration is 0.5-2 % DM, with a typical figure of 1.3 %.

Appendix 2

Conventional sewage system

Total electricity consumption at pump stations in the city of Uppsala (1993) = 4.5 GWh, including also electricity for heating and lighting the stations (pers. comm. Swedling, 1995). The amount of water passing through Kungsängens Sewage plant in 1993 = 21773300 m^3

Energy consumption = 4.5*1000000*3.6/21773300 = 0.8 MJ/ m^3

Vacuum sewage system (Östling, 1995)

Energy consumption in Bälinge = 289080 kWh/år
Number of persons = 2000
Production of waste water from toilets = 25-27 m^3/day

Energy consumption = 289080*3.6/(26*365) = 110 MJ/ m^3

Kitchen disposer (Nilsson, 1990)

Trademark	Disperator
Average working time	30 s
Number of runnings	2.4 times/day
Recommended water flow	5-7 l/min
Energy consumption	0.3 kW
Number of households	100 st
Persons	211 st

Water consumption = 30*2.4*6*100/(60*211) = 3.4 l/persons and day
Energy consumption = 30*2.4*0.3*365*100*3.6/(211*60*60) = 3.7 MJ/person and year

Appendix 3

Emissions at spreading (Egebäck et al., 1991)

The measurements of emissions were done on diesel engines with turbo chargers and power effects over 200 kW driving beside the road with high load. The figures are averages from measurements of 20-30 different engines.

Emissions in relation to the work done
HC 1.27 g/kWh
CO 3.53 g/kWh
NO_x 9.61 g/kWh
Diesel consumption 245 g/kWh
Energy content in diesel 43.1 MJ/kg
$N\text{-}NO_x = 0.45*NO_x$
1 kWh = 3.6 MJ

Efficiency = 1000/(245*43.1) = 0.34 => 34 %
Emissions in relation to the energy in the fuel
HC = 1.27/3.6*0.34 = 0.120 g/MJ
CO = 3.53/3.6*0.34 = 0.333 g/MJ
NO_x = 9.61/3.6*0.34*0.45 = 0.408 g/MJ