The ORWARE Simulation Model - Anaerobic Digestion and Sewage Plant Sub-Models

Magnus Dalemo

Akademisk avhandling för vinnande av agronomie licentiatsexamen kommer att offentligt presenteras vid ett seminarium i föreläsningssalen, Institutionen för lantbruksteknik, Sveriges lantbruksuniversitet, Uppsala, torsdagen den 12 december 1996, kl. 09.15. Seminarieledare: Tekn. Dr. Anne-Marie Tillman, Chalmers Tekniska Högskola, Göteborg.

ABSTRACT

The ORWARE model is intended as a tool for simulating different systems for handling organic liquid and solid waste in a densely populated area. The model includes truck transport, incineration, landfill, composting, anaerobic digestion, sewer transport, sewage plant, residue transport and spreading of residues on arable land. All physical flows in the model are described by the same variable vector including 43 substances. The output of the model consists of energy flows, emissions to air and water and the amount of residues returned to arable land, including pollutants and nutrients.

The development of an anaerobic digestion sub-model and sewage plant sub-model, included in the ORWARE-model, is described in detail. The anaerobic digestion sub-model included in ORWARE is based on a continuous, single-stage, mixed-tank reactor operating under mesophilic conditions. Degradation dynamics are calculated based on the substrate's composition of fat, protein and carbohydrates and the retention time. The sewage plant sub-model includes mechanical, biological and chemical purification of the wastewater, as well as anaerobic digestion and dewatering of the sewage sludge.

Evaluation of waste handling scenarios indicate, e.g., that source separation systems combined with biological treatment of the organic solid fraction generate lower environmental impacts and a higher recirculation of nutrients, but a lower energy turnover, compared with the incineration or landfilling.

Key Words: Systems Analysis, Integrated Waste Management, Organic Waste, Modelling, Anaerobic Digestion, Sewage Plant, Environmental Impact, Plant Nutrients Recirculation.

Swedish University of Agricultural Sciences,
Department of Agricultural Engineering
P.O. Box 7033, S-750 07 Uppsala, Sweden

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Abstract

A systems analysis of organic waste handling was carried out which included the development of a simulation model, called ORWARE. The model is used for quantitatively predicting the consequences of different management alternatives. The life-cycle assessment methodology was used for evaluation of the results. The development of an anaerobic digestion sub-model and sewage plant sub-model, included in the ORWARE-model, is described in detail.

The ORWARE model is intended as a tool for simulating different systems for handling organic liquid and solid waste in a densely populated area. The model includes truck transport, incineration, landfill, composting, anaerobic digestion, sewer transport, sewage plant, residue transport and spreading of residues on arable land. All physical flows in the model are described by the same variable vector including 43 substances. The output of the model consist of energy flows, emissions to air and water and the amount of residues returned to arable land, including pollutants and nutrients.

The anaerobic digestion sub-model included in ORWARE is based on a continuous, single-stage, mixed-tank reactor operating under mesophilic conditions. Degradation dynamics are calculated based on the substrate's composition of fat, protein and carbohydrates and the retention time. Therefore, the model is able to predict the gas production from a wide range of substrates and mixtures. The sewage plant sub-model includes mechanical, biological and chemical purification of the wastewater, as well as anaerobic digestion and dewatering of the sewage sludge. The model configuration is based on the sewage plant in Uppsala.

Five different scenarios have been simulated and the results are compared. The evaluation indicate that source separation systems combined with biological treatment of the organic solid fraction generate lower environmental impacts and a higher recirculation of nutrients, but a lower energy turnover, compared with the incineration or landfilling. Source separation and individual treatment of toilet fractions, such as urine, result in a high degree of nitrogen recirculation, but generates large quantities of material that has to be transported and spread.

Key words: Systems analysis, Integrated waste management, Organic waste, Modelling, Anaerobic digestion, Sewage plant, Environmental impact, Plant nutrients recirculation

CONTENTS

List of papers

The thesis consists of the following papers:

Paper I: Dalemo M., Sonesson U., Björklund A., Mingarini K., Frostell B., Jönsson H., Nybrant T., Sundqvist J-O., Thyselius L. 1996. The ORWARE-model, part 1, Model Description. (Submitted for publication).

Paper II: Sonesson U., Dalemo M., Mingarini K. & Jönsson H. 1996. The ORWARE-model, part 2, Case Study and Simulation Results. (Submitted for publication).

Paper III: Dalemo M. 1996. The Modelling of an Anaerobic Digestion Plant and a Sewage Plant, in the ORWARE Simulation Model. Report 213. The Swedish University of Agricultural Sciences, Department of Agricultural Engineering. Uppsala, Sweden.

Paper I describes the ORWARE-model, including the methods and model structure used. In Paper II, results from a case study using the ORWARE-model are presented. This includes simulation of five scenarios and a comparison of the results regarding environmental impact, energy ratio and recirculation of nutrients. In the last paper, Paper III, the modelling of the anaerobic digestion and sewage plant processes are described more thoroughly, regarding structure, assumptions and data used.

1. INTRODUCTION

The dramatic increase in waste production that has accompanied the emergence of modern society poses a threat to both human health and the environment. Therefore the Swedish Parliament has set a number of goals with regard to the handling of waste that should facilitate the development of sustainable production systems (NV, 1996).

- The content of environmental pollutants and other toxic substances in waste shall be reduced through changes in production.
- The quantity of waste shall be reduced through actions taken in the areas of both production and consumption.
- The waste shall primarily be reused or recycled
- High environmental standards shall be set for the handling of non-recoverable waste.
- The waste shall be handled in a ways that minimise adverse impacts on human health and the environment.

To achieve these goals requires that the waste be sorted, primarily at the source. Thus, it is intended that all waste have to be sorted prior to incineration or deposition in landfills.

Today around 40 % of the municipal solid waste is incinerated and 40 % is deposited in landfills. Source separation primarily involves batteries, paper and glass. The quantities of waste produced have also been reduced through recovery of packaging materials. Thus, the organic waste produced has become a major part of the remaining waste fraction. This fraction, containing nutrients and organic compounds, can have serious environmental impacts, especially when it used as landfill. The disposal of sludge from sewage plants poses similar problems. There has, consequently, been an increase interest addressing source separation and the development of new methods for treating both the solid and liquid organic waste fractions. The purpose has then been to develop environmentally sound waste-disposal systems and to facilitate the return of organic material to farmland.

Organic waste management systems are complex. A wide variety of waste fractions are generated, and many types of collection and treatments methods are available. Thus, for example, when introducing new systems there is a risk that although emissions in connection with waste treatment can be reduced, transport-related emissions will increase, resulting in a higher total environmental impact.

In the face of this complexity, a standard method is needed for evaluating different systems for handling organic waste. In the following section of this thesis, existing methods for evaluating and modelling waste handling systems are briefly reviewed.

Other waste handling studies

Several analyses have been made in the area of waste handling. Riggle (1993) describes two commercial models, WastePlan and RecyclePro, which deal with the economics of different waste management systems. Furthermore, Sundberg (1993) developed an optimisation model, MIMES/WASTE, that considers not only economics but energy and environmental effects as well. More comprehensive systems analyses focusing on environmental effects have been carried out by Gupta & Shepheard (1992) and White et al. (1995). These analyses considered the environmental effects, economics and energy flows associated with a number of different scenarios for municipal solid waste management. In both these projects spreadsheet models were also presented.

The MIMES/WASTE model focuses mainly on integrated material and energy flows, but also deals with economics and the emissions of a small number substances with negative environmental impacts. The model can be used both for optimising and simulating scenarios for handling municipal solid waste. Furthermore, it is able to model source separation of a large number of fractions. Although the consequences of transportation and processing are included, emissions in connection with the deposition and recovery of waste fractions are not.

The systems analysis of municipal solid waste management in Gupta & Shepheard is based on a life-cycle assessment approach. The analysis includes the energy flows, environmental impacts and economics associated with landfilling, combustion for energy recovery, production of refuse-derived fuel, collection/separation of recyclables and composting. Anaerobic digestion was not dealt with because not enough data were available. The time frame covered in the analysis is 20 years, which limits the evaluation of environmental impact caused by landfilling. The analysis considers alternatives including the source separation of yard waste and recyclables, such as paper, cardboard, glass, metal and plastics, but does not deal with the separation of an organic fraction.

The life-cycle inventory in White et al. (1995) deals with both household and commercial solid waste fractions that are mixed or source separated. Included in the study are transportation, central sorting, and treatment processes such as thermal treatment, anaerobic digestion, composting and landfilling. The output of the analysis are energy, secondary materials, compost, final inert waste and emissions to air and water. The economics of the system are also included. The waste is followed until it becomes inert landfill material or is converted into compounds that are emitted to the atmosphere or surrounding water or leave the system as a valuable product. Hence, the further consequences of material recovery and compost recirculation are not included.

Systems analysis of organic waste

The main advantage of the biological treatment of organic waste is that it enables the recirculation of nutrients to farmland. However, emissions are produced in connection with the transport and spreading of residues. Quantities of residues vary depending on the treatment method. The extent of the transport work required depends on the degree of access to farmland around the city and on the total quantity of residuals. It is therefore important to include both the solid and liquid fractions in the same study

Effects of emissions from the organic fraction in landfill are of great importance owing to nutrient leaching and the large amounts of methane released to the atmosphere. Phosphorus in the landfill poses an especially serious eutrophication problem in the long term.

No one of the analysis methods found takes both the transport and spreading of residues into account. Furthermore, the overall consequences of landfilling are not treated in the analyses found in the literature. Therefore, a special systems analysis of the solid and liquid organic waste fractions with a model developed for this purpose seemed to be necessary. A project called "Systems Analysis of Organic Waste" were therefore initiated. The project was a collaboration between the Swedish Institute of Agricultural Engineering, The Swedish University of Agricultural Sciences, The Royal Institute of Technology, and The Swedish Environmental Institute and the content in this thesis is a result of the project.

2. SYSTEMS ANALYSIS

Systems analysis can be used to increase the understanding of a system and help decision-makers to more effectively choose from among a number of different alternatives . Systems analysis places emphasis on a holistic approach to waste management problems by focusing on the structure of a system and the relations between its various parts.

For a system analysis to produce worthwhile data, it must be based on solid scientific knowledge of the problem. The methodology of systems analysis can be divided into a number of steps (Figure 1). These steps are not separate from each other and in most cases have to be carried out in an iterative process. In the following section these steps are briefly explained and discussed from the perspective of the present study on the handling of organic waste.

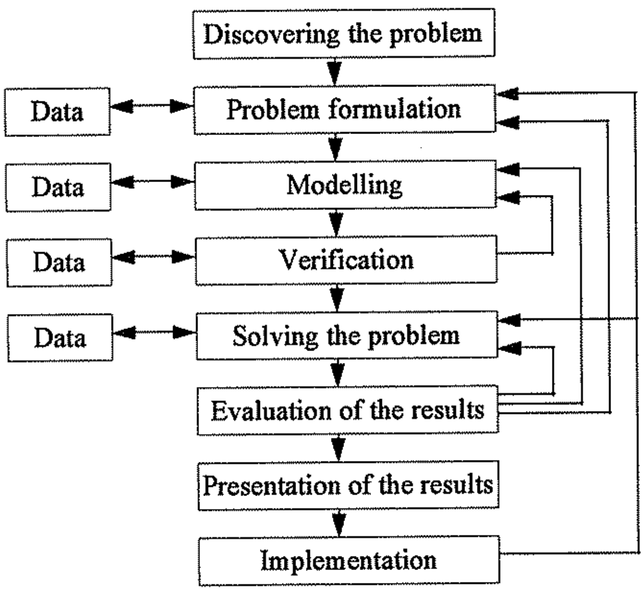

Figure 1. The systems analysis work is an iterative process including a number of different actions (Gustafsson et al., 1982).

3. PROBLEM FORMULATION

An accurate and precise formulation of the problem is one of the most important prerequisites in systems analysis. Problem formulation can be divided into the two parts: formulating the goal and defining the system boundaries.

Goal definition

Our basic hypothesis was that today's systems of handling organic waste are not optimal. Thus the purpose of our project was to identify handling systems that have a lower environmental impact while recirculating nutrients to a higher degree.

Later in the project the goal was defined more specifically as the development of handling systems that contribute less to greenhouse gases, acidification, eutrophication, photooxidant formation, human health risks and ecotoxicological impacts (aquatic and soil) while offering a higher degree of energy turnover and nutrient recirculation. The formulation of these goals was facilitated by using life-cycle assesment (LCA) methodology.

Additional goals were:

- to identify priorities for research and development in the area of organic waste handling and treatment,
- to construct a model that could be used for evaluating different organic waste management scenarios covering several densely populated geographical areas,
- to construct a model useful as an educational tool.

System boundaries

In systems analysis the choice of system boundaries is very important. Boundaries determine the amount of work involved in data collection and also influence the results of the simulation and their interpretation.

When comparing different alternatives in a life-cycle analysis the system boundaries are defined by formulating one or more functional units that the systems must fulfil in order to be comparable. In this study, the functional unit was formulated as a system for taking care of the organic waste produced in a certain area.

Activities dealt with in the model include the collection and transport of waste fractions, treatment of waste and the recirculation or final disposal of residues. The recirculation of compost and sludge, for example, includes long-distance transport and spreading operations on farmland, but does not include post-spreading environmental impacts of the residues. Environmental impact from landfilling of material included in the model, are those occurring until the material is entirely spread to the environment through air or water emissions. These emissions are divided in two time frames, a short surveyable time (ca 100 years) and an infinite remaining time.

Selecting the waste fractions to be included in the term "organic waste", to be included in the study was difficult. Finally a pragmatic definition was formulated where the goal of improving recirculation was addressed. Organic waste included in the project was then defined as "wastes coming from living organisms that are essentially free from synthetic components and for which the present recovery and recirculation system can be improved". These wastes are:

- wastewater received at the sewage plant,
- organic wastes from private homes, businesses and industries,
- park and garden wastes.

The geographical boundaries were set so as to include the area connected to the public sewage system in the densely populated area studied. This geographical boundary applies to the waste production sites but not to the waste treatment activities or the spreading of residues which were conducted outside this area.

Only direct emissions from the handling of organic waste are included. For example, emissions produced in connection with constructing infrastructure and buildings are not included. The only emissions included from transport models are those to the atmosphere. Emissions related to the production of heat and electricity in scenarios with net heat and electricity consumption are not included in the model.

4. MODELLING

A model can be used for improving one's understanding of complex systems, making predictions and teaching, as well as for process control or design.

To analyse systems for managing organic waste, a computer model called ORWARE (Organic Waste Research model) was constructed (Paper I). This model calculates energy flows, plant nutrient flows and emissions to air, water and soil (figure 2). The sub-models included in the ORWARE model are as follows:

- Transportation (Sonesson, 1996)
- Sewage systems (Paper III)
- Sewage plant (Paper III)
- Anaerobic digestion (Paper III)
- Incineration (Mingarini, 1996)
- Landfilling (Mingarini, 1996)
- Composting (Sonesson, 1996)
- Transport distances for residues to arable land (Sonesson, 1996)
- Spreading of residues (Paper III)

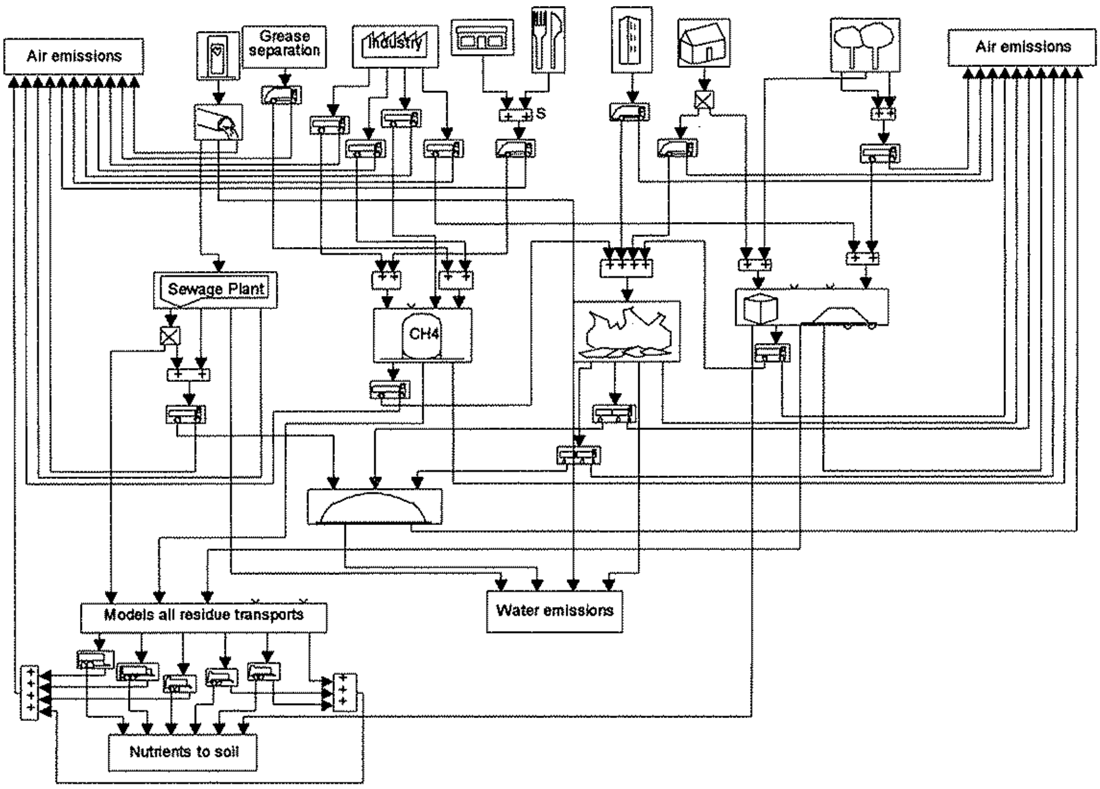

Figure 2. An example of a scenario for handling organic waste with the ORWARE model.

Choice of model type

The ORWARE model is in most parts a linear mathematical model. However, since it also includes some non-linear relations it is classified as non-linear.

Mathematical models can also be classified as dynamic or static. The data describing the composition and quantity of organic waste fractions are presented as average values over the year. The ORWARE model was made using a static approach, since the input flows were approximated to be constant. Furthermore, a dynamic model requires much more knowledge about structure and more parameters compared with a static model. Such information is lacking for many of the included processes.

The model is implemented on a computer platform, MATLAB/Simulink (Maths Inc., 1993). This program has a graphical interface with a hierarchical structure. The language has few limitations regarding model type and complexity.

Model structure

All processes are constructed based on the same principle structure. The consumption of energy and resources, production of energy, emissions to air and water, and residual effluent are related to the quantity and composition of the material flow to the model (figure 3). This model structure is used for all process parts, though in many sub-processes one or more of these flows can be zero.

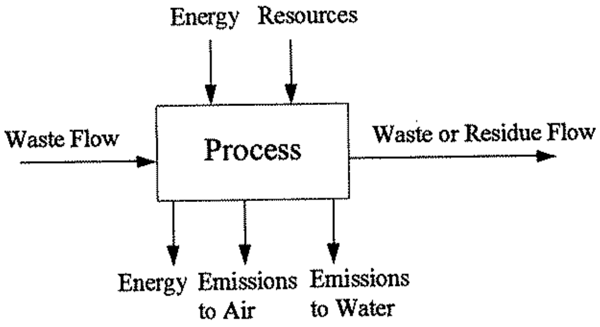

Figure 3. A general description of a process model

The waste flow is a signal to the process, and all the other flows are calculated from this waste flow. The principles used when relating the flows to the influent waste flow depend on the complexity and information found about the structure and parameters. The four types of principles used in the construction of the sub-models in ORWARE are:

- Mechanistic: description based on natural laws,
- Empiric: description based on statistical studies,
- Measurements: description without statistical studies,
- Plausible assumptions.

The last three are examples of black box modelling where the relations are established based on studies without knowing the underlying details of natural laws.

Description principles

All flows in the model are described with a vector of the same structure (Table 1). However, energy flows are handled separately. Parameters to be included in the vector had to meet at least one of the following three selection criteria:

- important for the environment,
- important for the processes,
- of economic value.

Table 1. Substances included in the vector used in the ORWARE model

C-tot	Dry matter	PCB	NOx	Cu
Slowly degradable organics (chsd)	CO_2	PAH	N_2O	Cr
Moderately degradable carbohydrates (chmd)	CO_2 (fossil)	Phenols	S-tot	Ni
Rapidly degradable carbohydrates (chfd)	CO	O-tot	SOx	Zn
Fat	CH_4	H-tot	Cl	Hg
Protein	VOC	H_2O	P	Cd
BOD_7	AOX	N-tot	K	Particles
COD	CHX	NH_3/NH_4^+	Ca	
Volatile substance	Dioxins	NO_3^-	Pb	

Sub-models

The two sub-models in ORWARE that I developed are the anaerobic digestion model and the sewage plant model. The digestion model is intended to be used both for solid organic waste and sewage sludge. The sewage plant model represents a plant that carries out the mechanical, biological and chemical purification of wastewater. The anaerobic digestion and sewage plant models are briefly described in the following sections. A more thorough description of the structure, assumptions and data in the models can be found in paper III.

Anaerobic digestion

Several anaerobic digestion models can be found in the literature and include both dynamic (Dunn et al., 1994) and static (Legrand et al., 1990) types. However, none of these models are relating the degradation of organic materials to their composition only, but knowledge regarding the type of material and its origin is also needed. By relating the degradation of a given substrate to its composition, the gas production from a wide range of substrates and mixtures can be predicted. The present anaerobic model is based on a continuous, single-stage, mixed-tank reactor (C.S.T.R.) operating at a mesophilic temperature.

The model has four entrances owing to the different pretreatment needs (figure 4). The pretreatment processes are hygienisation (heating to 70° or 130° C), maceration and separation of metal and plastics. All these processes result in energy consumption. The separation of metal and plastics includes also a loss of organic materials.

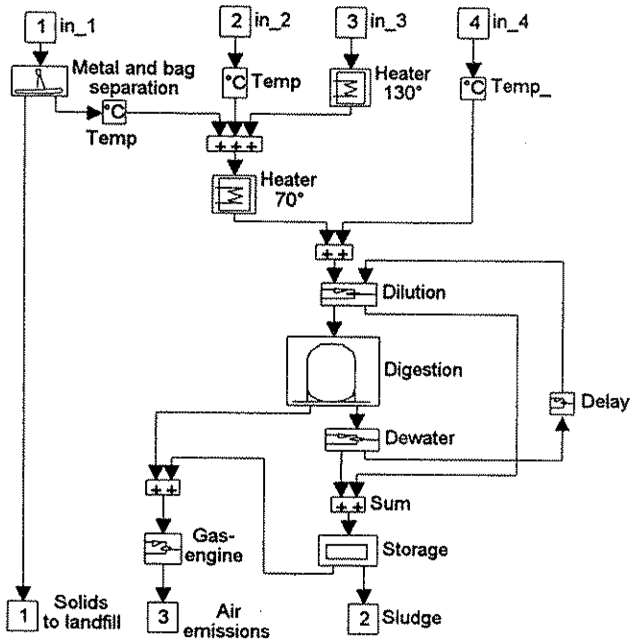

Figure 4. The anaerobic digestion sub-model in ORWARE.

The waste often needs to be diluted, reaching the normal dry matter content of 3-10 % for slurry processes. The dilution can be accomplished by adding water or circulating liquid from the effluent.

The degradation is calculated from the influent substrate and the hydraulic retention time (R) in the digester by using the formula (Legrande et al., 1988):

$D = D_0 / (1 + 1/(k*R))$

D = degradation ratio ($0<D<D_0$)
D_0 = maximum degradation ratio ($0<D_0<1$)
k = first-order rate constant (days^{-1})
R = hydraulic retention time (days)

The degradation ratio is calculated for the different organic compounds with specific values for D_0 and k. Furthermore, the production of methane and carbon dioxide is calculated from the degradation ratio related to each digested organic compound.

$B_{CH4}=\Sigma\ m_n \cdot D_n \cdot 16/12 \cdot C_n$
$B_{CO2}=\Sigma\ (1-m_n) \cdot D_n \cdot 44/12 \cdot C_n$

B = Gas production [kg/year]
n = (chsd, chmd, chfd, fat, protein)
D_n = degradation ratio ($0<D_n<D_0$)
m_n = methane ratio [%-volume]
C_n = carbon in the substrate [kg/year]

Table 2. Degradation of organic substances (Dalemo, 1996)

Organic substances	Maximum degradation, D_0	Rate constant, k days^{-1}	Methane, m %
Slowly degradable organics (chsd)	0	0.001	50
Moderate degrad. carbohydrates (chmd)	1.0 - 1.77*chsd	0.18	50
Rapidly degradable carbohydrates (chfd)	1.0	0.23	50
Protein	0.80	0.13	69
Fat (after hygienisation)	0.95	0.13	78

It is assumed that organically bound nitrogen and sulphur are found in the proteins. They are mineralised in amounts proportional to the degradation ratio for the protein, forming ammonium and hydrogen sulphide, respectively. After digestion the sludge is stored in large, covered lagoons. This makes it is possible to recover methane produced during storage. A small amount of ammonia is emitted during storage.

Electricity and heat are consumed in the plant. The electricity consumption is around 5 % of the energy in the produced gas. The amount of heat consumed by hygienisation and digestion is calculated using mechanistic models that take retention times and reactor geometry into account. A heat exchanger with a 50 % efficiency is also included. The gas produced, are combusted in a stationary engine resulting in 30 % electricity, 60 % heat, and the remaining 10 % is lost. In addition, combustion of the gas generates emissions of CO_2, SO_2, NO_X, CO and VOC (primarily methane).

Sewage plant

Models of sewage plant processes found in the literature are very detailed and contain a large number of parameters (e.g. Hellström & Rennerfelt, 1993). The present model was designed to calculate the emissions and energy flows for the processes in a sewage plant, without detailed knowledge of basin volumes or sludge retention time. The model is based largely on the layout of the Kungsängen plant in Uppsala (figure 5).

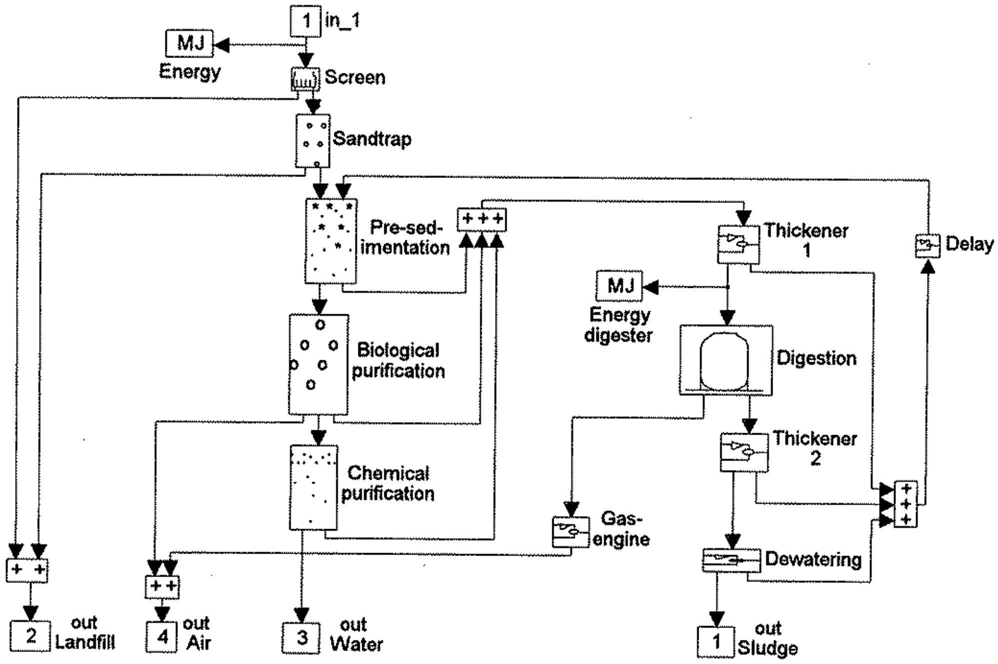

Figure 5. The sewage plant sub-model included in ORWARE.

The models describing the activated sludge process, the nitrification/denitrification process and the chemical phosphorus removal process are basically mechanistic. Studies on sedimentation and dewatering processes focus on dry matter (DM), volatile solids (VS) and suspended solids (SS). Therefore, the modelling of these substances can be based on measurement data found in the literature. However, measured values for most of the remaining substances in the ORWARE vector have not been found. These substances were therefore assumed to be either dissolved in the liquid or attached to suspended solids when separating a solid fraction from a liquid, e.g. in the clarifiers or thickeners (Table 3). Substances assumed to be water soluble are removed in relation to the water separated and the others in relation to the suspended solids.

Table 3. Substances assumed to be soluble in water and attached to particles respectively

Attached to particles	Water soluble
All organic compounds	NH_4^+
N-organisation	NO_3^-
S-tot	Cl
P-tot	K*
Ca*	
Heavy metals *	

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

The wastewater is first purified, to remove large, suspended solids and heavy particles, by passing it through the screen and sand trap.

The first main purification process in the sewage plant is the presedimentation. The quantity of suspended solids and water separated is related to the suspended solids in the influent and the precipitation method used. Furthermore, the other substances are related to the fraction of suspended solids or water separated. However, for the separation of heavy metals, special measurements are used.

The biological purification is modelled as an activated sludge-treatment process. Based on the total BOD_7 reduction the amounts of oxygen and carbon consumed through assimilation and oxidation are calculated. The assimilation also involves production of around 0.75 kg SS/kg BOD_7. The activated sludge model also results in emissions of ammonia and N_2O. Sludge separated from the biological treatment is modelled in the same way as in the presedimentation.

The model offers the choice of including nitrogen removal in the sewage plant through nitrification and denitrification. From the prescribed nitrogen reduction, the nitrogen emitted, organic carbon degraded and aeration needed (30 % in surplus) are calculated from the chemical formula:

$$NH_4^+ + 2O_2 + 5/4C \dashrightarrow 1/2N_2 + 5/4CO_2 + 3/2H_2O + H^+$$

Nitrogen purification results in higher levels of nitrate and lower levels of ammonium in the effluent. Furthermore, emissions of N_2O are increased.

Phosphorus is primarily removed through chemical precipitation. In the model, phosphorus is removed by addition of ferrous chloride in the presedimentation. The quantity of suspended solids formed through precipitation is calculated using the formula:

$$Fe^{3+} + 3OH^- + HPO_4^{2-} \dashrightarrow FePO_4 + Fe(OH)_3 + H^+$$

The separation of sludge from the chemical purification is modelled in the same way as in the presedimentation.

The sludge treatment first includes a thickener followed by a digester, another thickener and, finally, a dewatering treatment. Sludges from all three purification stages are treated together. The thickener and dewatering processes are modelled using the dry matter content of the sludge expected after each respective process. All other substances, are as previously, calculated from the fraction of suspended solids or water separated in relation to the influent. The digester works in the same way as the one in the anaerobic digestion plant, except that the formation of hydrogen sulphide is lower owing to the chemical precipitation. Combustion of produced gas in a stationary engine is also included in the model.

The energy used in the plant is divided in electricity to aeration, calculated from the volume of air needed, and electricity for other use, calculated from the size of the plant. Furthermore heat, consumed for heating the digester, is related to the volume of digested material (Dalemo, 1996).

Validity ranges

The entire ORWARE model is generally applicable under the conditions included in the sub-models validity range. The validity range for the anaerobic digestion model and the sewage plant model are presented in the following section. Validity ranges for the other models are found in paper I.

The anaerobic digestion model is largely general for digestion in a C.S.T.R. under mesophilic conditions. Adaption of the model to other temperatures and digestion methods would include changes in parameters and for some alternatives also the structure. Plants with other process configurations e.g. pretreatment processes, would primarily influence the energy consumption. The model is valid for digestion of a wide range of substrates, except for digestion of highly diluted or concentrated materials.

The sewage plant model can be used for plants with mechanical sedimentation, activated sludge, and chemical phosphorus removal. However, adapting of the model to the actual situation is necessary. The primary part of the information needed, can be found in official reports from the plants. The model is constructed for treatment of a ordinary municipal wastewater, though minor variations in composition can be handled.

5. VERIFICATION

The purpose with verification is to determine if the model is useful for the purpose of the project. The verification process can be divided into different parts. This section provides an overview of the verification of data, the hypothesis and the technical aspects.

Data

The accessibility of relevant data varies for the different processes in the model. Furthermore, it has generally been a problem to find data relating emissions from the processes to the treated waste. Often the emission data found relate emissions to a concentration in water or air because regulations are usually formulated as maximum concentration levels. Another part of mode for which data are limited concerns the composition of generated waste fractions. The scarcity of this type of data is probably due to the fact that composition varies in time and space, and measurement problems often arise owing to the inhomogenity of the material.

The data sources used in the model can be classified into three groups:

- scientific papers,
- reports,
- personal communications.

Hypothesis

A test of the hypothesis includes a control of the assessments of structure and function, etc. For the ORWARE model this has been done by comparing results from the process models with observations on the real system.

For the anaerobic digestion sub-model no literature has been found that can confirm the accuracy of the method used for calculating gas production. Cynowet et al. (1993) reported on experiments aimed at relating the maximum degradation ratios and rate constants of materials to their respective organic compositions. They did not found any correlations except for lignin content. However, when comparing gas production from the model with literature figures, the level of agreement obtained was considered to be good (paper III).

The basic approach in modelling the sewage plant has been to separate substances assumed to follow the water from those assumed to follow the suspended solids. These assumptions were based on their respective solubility in water. For most substances this seemed to be a good approximation. However, the results for potassium, assumed to be soluble in water, and for calcium, assumed to follow the suspended solids, were inaccurate; since their concentration in the sludge produced was underestimated and overestimated respectively. The separation characteristics of these substances were therefore adjusted to match measured data.

Further sensitivity analyses and case studies have to be made in order to determine where more detail needs to be added in the model.

Technical verification

A technical validation is necessary in order to detect programming bugs and other logical defects.

Once the main part of the process of developing the sub-models was finished, similar models were constructed as spreadsheets in Excel. Calculation results from the SIMULINK/MATLAB models were then compared with those from the Excel models and some programming defects were detected by this process.

Total verification

A total verification of the model is impossible of practical reasons, since total emissions from the organic waste management system calculated in the model can not be compared with measurements of the real system. The verification of the total model is built upon verification of the sub-models and a general estimation of the probableness of the total results, including contact with experts.

A sensitivity analysis of the ORWARE model have also been conducted. As the model is essentially linear, the sensitivity analysis was concentrated on the calculations of emiddions having major influences on the result, both from the sub-models and the entire model. Efforts have been made to improve the most important parts of the model, by better data and a more detailed structure.

6. SIMULATION

The ORWARE model is designed to evaluate conceivable organic waste handling systems, with the ultimate aim of developing systems with a low environmental impact, a high degree of recirculation of plant nutrients, and a high energy turnover. This is facilitated by simulation of alternative scenarios concerning the handling of organic waste. No optimisation functions are included in the model. Therefore, to find the best solutions the simulation scenarios have to be carefully planned.

The scenarios can be chosen based on different criterions. They be can considered as:

- probable scenarios, that are likely to be realised,
- desirable scenarios, with respect to environmental impact, recirculation etc.

The probable scenarios are likely to be realised in the near future, while the desirable scenarios are the target aimed at in the long run.

There are also some objectives to be kept in mind from the evaluation point of view. The evaluation is facilitated if only one thing is changed in a time between scenarios. However, it is also important to keep the number of scenarios low, limiting the time consumed for evaluation.

7. RESULTS AND DISCUSSION

The ORWARE-model generates a large amount of data describing emissions and flows of energy and nutrients. An important part of the work is therefore to transform all these data into useful results.

Evaluation method

The LCA-methodology is used to add the emission figures to environmental effect categories which, together with production and consumption of heat, electricity and oil, and the return of nitrogen and phosphorus to arable land, are the basis for evaluating the results.

Methods for aggregation of emissions to form environmental loads were proposed in the LCA Nordic (1995). These have been somewhat modified for presentation of the results from simulation of the organic waste handling system with the ORWARE model.

- Global Warming [CO_2-equivalents]. Figures given for a time horizon of 100 years are used. The main substances contributing to the impact are CO_2, CO, VOC, NO_X and N_2O. For methane a time perspective of 100 years is used, resulting in a weighting factor of 11.
- Health effect [kg contaminated body weight]. For this effect the CML provisional method is used (Heijungs et al., 1992). Emissions to air, water and soil are added to obtain a total health effect. The majority of substances are included in this effect category. However, the emissions to air are the greater part of the contribution to health effects.

- Acidification [kmol H^+]. Depends not only on the emitted substances but also on the receiving soil. Therefore it is useful to calculate effects for both minimum and maximum cases. In the minimum case only SO_2 and HCl contribute to acidification, while in the maximum case NO_X and NH_3 contribute as well.
- Eutrophication [kg O_2-equivalents]. A maximum case is used with both nitrogen and phosphorus compounds contributing, as suggested by Finnveden et al. (1992). The substances are COD, P-tot, NH_4^+, and NO_3^- to water, and NH_3 and NO_X to air.
- Photochemical oxidants [kg ethene-equivalents and kg NO_X]. CHCl, CO and VOC have been weighted as ethene-equivalents. NO_X also results in the formation of photochemical oxidants but cannot be weighted as ethene-equivalents. The formation of photochemical oxidants is therefore presented in two parts.
- Ecotoxicity [kg soil and m^3 water]. This consists of many complex effects on living organisms in water and soil. It is in principle possible to calculate ecotoxicity in water and soil separately, but they can not be added together. This category has not been included so far.
- Ozone depletion due to CFCs, VOC and N_2O, etc. Emissions of CFCs from the studied system are negligible, and no satisfactory weighting factors have been found for the other substances. This category is therefore not included in the evaluation.

In LCA it is often common to reduce the parameters to only one index. However, all environmental effect categories can be considered as local or regional, except for the global warming and ozone depletion effects which are global. We have therefore considered it as the task of decision-makers to ranking the studied alternatives based on the particular situation that they are faced with.

The results can be presented in diagrams on different levels. For each effect category a diagram can facilitate comparisons of :

- the contribution from different activities in one scenario (figure 6).
- the total contribution from the scenarios studied (figure 7).

Finally all scenarios and effect categories can be presented in one diagram, if expressed in relative values (figure 8).

This graphic representation of results can be complemented by calculating a large number of other parameters of interest for the evaluation of the studied scenario alternatives. Examples of these are the total transport work, the ratio of energy in oil required for transport to the biogas produced, Data on scarce natural resources consumed are also important when comparing scenarios and can be extracted from the simulations.

Evaluation of scenarios

In paper II, five scenarios were studied. In the scenario 3 and 4, the organic waste fraction is source separated, while in the scenario 1, 2 and 5 the organic solid fraction is transported and processed together with other waste fractions.

- Scenario 1. **Incineration** of organic solid waste. Wastewater treatment in a sewage plant. Landfilling of grease water. Composting of park waste.

- Scenario 2. **Landfilling** of organic solid waste and grease water. Wastewater treatment in a sewage plant. Composting of park waste
- Scenario 3. **Anaerobic digestion** of organic solid waste and grease water. Wastewater treatment in a sewage plant. Composting of park waste.
- Scenario 4. Reactor **composting** of organic solid waste and park waste, together with straw. Wastewater treatment in a sewage plant.
- Scenario 5. **Incineration** of organic solid waste. **Urine separation** and conventional treatment of the remaining wastewater fraction in a sewage plant. Landfilling of grease water.

In the following section an example of results is presented focused on the global warming effect and the anaerobic digestion scenario (scenario 3).

The emissions of gases contributing to global warming from the anaerobic digestion scenario, are weighted in CO_2-equivalents and presented in figure 6. It indicates that emission of NO_X is the major contribution from the anaerobic digestion process. The treatment of wastewater in a sewage plant is the activity with the largest contribution to the global warming effect, primarily through emissions of NO_X and N_2O. The emissions produced in connection with composting are low since only the park waste is composted in this scenario. Collection of the waste, and the transport and spreading of residuals result in emissions of the same magnitudes, both with CO_2 as the major contributing substance.

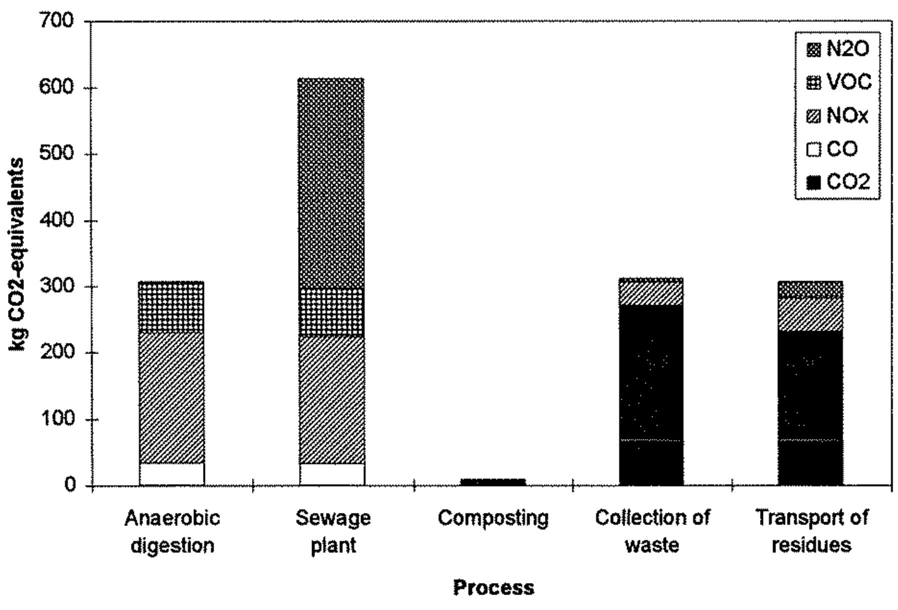

Figure 6. Emissions of greenhouse gases, weighted in CO_2-equivalents, for the anaerobic digestion scenario (scenario 3) in paper II.

Compared with other scenarios, the total emissions of global warming gases from the anaerobic digestion scenario (3) are quite low (Figure 7). Emissions associated with transport are higher in this scenario than in the incineration (1) and landfilling (2) scenarios. However, emissions from the processing of solid waste in the digester are significantly lower than in these scenarios. Emissions associated with the composting scenario (4) are even lower. Urine separation (5) reduces the emissions from the sewage system, but result in increased transport-related emissions. The high impact of landfilling is primarily due to emissions of methane, even though 50 % of the gas is collected.

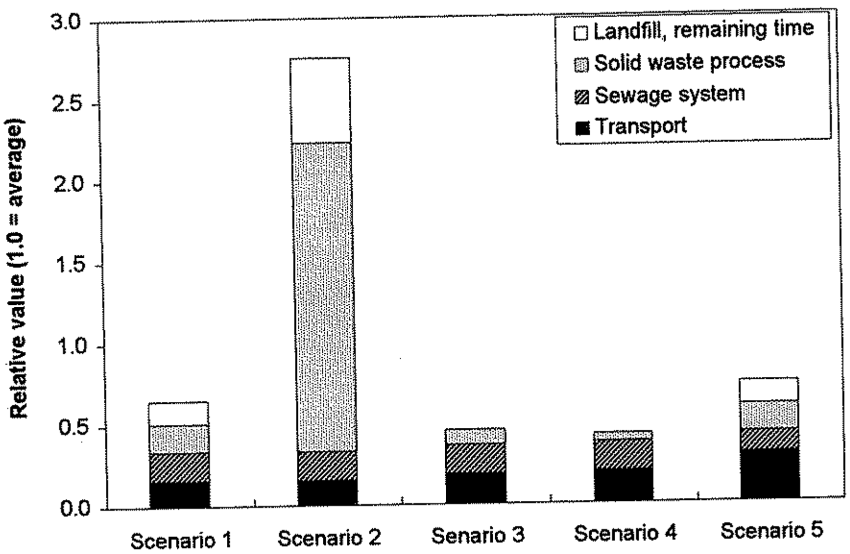

Figure 7. Comparison of the global warming effect from the scenatios.

The major treatments methods for organic waste in Sweden today are landfilling or incineration for the solid fraction and treatment of wastewater in a sewage plant. The goal with the systems analysis of organic waste was to find new methods for handling the organic waste that have lower environmental impacts, a higher energy ratio and a higher nutrient recirculation efficiency. Therefore, the future scenarios 3-5 are compared with scenario 1 and 2 for all the effect categories.

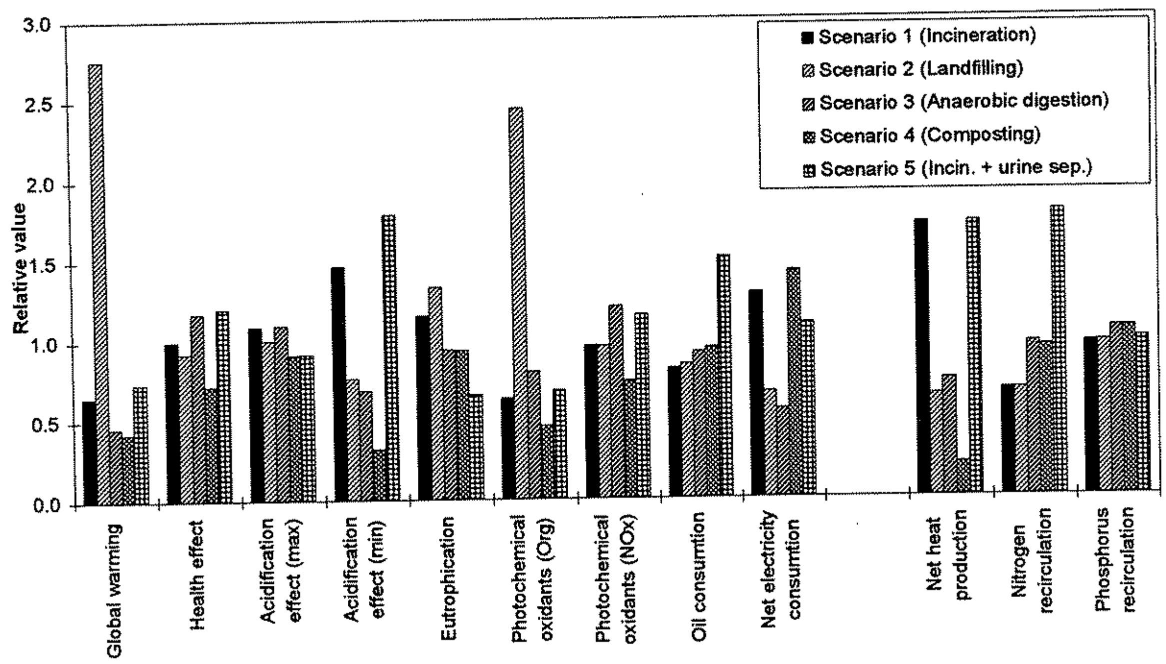

Figure 8. A comparison of the scenarios for all the studied categories.

Based on the goals for systems analysis of organic waste handling systems, it can be concluded that:

- None of the new handling scenarios studied meet all of the criteria set for the new waste handling system.
- The composting scenario results in lower emissions of all studied environmental pollutants and a higher return of both nitrogen and phosphorus, compared with both the incineration and landfilling scenarios. However, the energy ratios of oil, electricity and heat are lower for the composting scenario.
- The anaerobic digestion scenario meets the criteria set for nitrogen and phosphorus recirculation, electricity ratio, and contribution to global warming, eutrophication and acidification (min), but not the criteria for the remaining environmental effects and the oil and heat ratios.
- Separation of urine in a scenario with incineration of the solid fraction results primarily in a higher return of nitrogen and a lower eutrophication effect compared with the scenario where the whole wastewater fraction is treated in a sewage plant. Urine separation also results in a lower oil ratio owing to increased transport.

System boundaries

The systems analysis indicated that the composting scenario is characterised by a high degree of nutrient recirculation and low environmental impacts but at the cost of a low energy ratio. In the anaerobic digestion scenario the energy ratio was significantly higher and nutrient recirculation was high, but so were environmental impacts. Hence, every system solution is a compromise between the level of environmental impact and energy use.

The differences in energy-requirement in the scenarios is converted to emissions by using energy sources outside the system. Only the emissions from the differences in net electricity and net heat, need or production, between the scenarios have to be included. However, the type of fuel/substrate used for producing heat and electricity has a large impact on the emissions. The emissions from oil combustion is already included in the model. Another aspect to be considered is that if the gas produced from the waste is used for vehicle fuel instead of electricity production or heat production, total emissions will be reduced (Nybrant et. al. 1996).

In the same way as energy, the amounts of recirculated nitrogen and phosphorus to soil could be transformed to environmental impact by including emissions produced in connection with production of chemical fertilisers, that all scenarios producing the same quantity of nutrients to soil. The energy consumption and emissions associated with the production of nitrogen fertiliser significantly influence the results, while the corresponding effects associated with the production of phosphorus fertiliser are marginal. However, the production of phosphorus in connection with mining should be viewed more as a conservation problem (it has been estimated that this limited natural resource will be used up in about 50-100 years).

It is essential that the organic residues are recirculated, since otherwise they will be disposed on the landfill, where the nutrients will contribute to the eutrophication effect, and the carbon will give rise to methane emissions that could contribute substantially to global warming.

This is especially true in the case where a large quantity of sludge from a sewage plant is disposed of on a landfill instead of being spread on farmland (Nybrant et. al. 1996).

Total contribution

Interest here is focused not only on the ranking of alternatives, but also on the total environmental impact of the activities connected with handling organic waste. In the case study made in Västmanlands County emissions of CO_2, SO_2 and NO_X, from the handling of municipal solid waste were compared with corresponding estimated total emissions in the area. In this case waste handling accounted for between 0.5 and 1.0 % (Dalemo & Oostra, 1996).

To compare future alternatives with the reference alternative the predicted change in emission levels can be compared with the environmental goals set by the government. A first attempt to determine whether environmental goals could be reached in the area of organic waste by changing the handling system was made in the Uppsala case study (Hellstrand, 1996).

8. CONCLUSIONS

The systems analysis of organic waste was undertaken with the main aim of verifying the hypotheses that organic waste is managed in a sub-optimal way. There was a strong belief that a systems approach was necessary to analyse the complicated way organic wastes are collected, treated and disposed of. Both solid and liquid organic waste fractions have been considered. Furthermore, environmental impact, flows of energy as well as plant nutrients have been evaluated for the organic waste systems. Several general advantages with the systems analysis method used, including the ORWARE model and evaluation using the LCA methodology, have been found. The most important are:

- The method is a help in structuring and enclosing the problem,
- It is generally applicable. However, it is necessary with adaptation of parameters for the specific conditions in the studied area,
- Both existing and future scenarios can be evaluated,
- A wide range of substances and effect categories can be evaluated,
- Result diagrams on different levels can easily be presented,
- The number of evaluation parameters is reduced by using the LCA-methodology,
- The final ranking of alternatives is left to the decision-makers on the basis of the situation in the studied area.

However, some objectives have to be remembered. The number of scenarios have to be kept low, both limiting the time consumed for the evaluation process and facilitating the decision-makers final ranking of alternatives. The selection of appropriate scenarios is of course also important. Furthermore, it is difficult to define and apply appropriate system borders. When using a computer model it is also easy to forget aspects of importance not included in the model, e.g. socio-economic factors. It is also important to observe that the method is not intended for evaluation of sustainability, but for comparison of scenarios.

The ORWARE model is considered to be versatile and produces useful information for evaluating handling systems for organic waste. Strengths (+) and weaknesses (-) with the outline of the existing ORWARE model are:

+ A wide range of substances are included in the model
+ Handling alternatives both for liquid and solid organic fractions can be examined,
+ Useful for identification of activities with high environmental impact on a system,
+ Includes the spreading of residues, both from solid and liquid organic waste fractions,
+ Environmental effects from landfilling are included,
- No warning system when using the model outside the validity range,
- Data are lacking in some parts, therefore assumptions have been necessary,
- The system boundary with organic waste is not always natural,
- Economic considerations are not included,
- Evaluation of rural areas is not possible due to lack of relevant transport and wastewater models.

The following applies to the anaerobic digestion model included in ORWARE:
+ Possible to calculate the gas production from a wide range of substrates and mixtures,
+ Easy to adapt for different plant configurations,
- Scientific references for the calculation method of gas production has not been found,
- Only C.S.T.R. digestion is included in the model.

The following applies to the sewage plant model included in ORWARE:
+ Adaptation to specific plants is primarily done from official reports,
+ Easy to follow the flows in the model since it is divided in the primary purification processes,
- The model is not verified for treating a wastewater fraction where urine and faeces are removed.

9. FUTURE RESEARCH AND DEVELOPMENT

One part of the future development of the ORWARE simulation model is through case studies. The model has so far been applied for evaluation of organic waste handling systems in Uppsala city (Nybrant et al., 1996). Furthermore, it has been used when planning the handling systems for municipal solid waste in the region of Västmanland (Dalemo & Oostra, 1996). At the moment it is being used in a project in Stockholm, getting a comprehensive view of the waste-handling system of today as well as future alternatives. The projects are performed in co-operation with local athorities and waste-handling companies.

The ORWARE model is also intended to be developed, to include economic considerations and optimisation possibilities. The model will also be extended to include other wastes, besides the organic fraction, within the municipalitie's responsability.

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