The ORWARE Simulation Model

- Compost and Transport Sub-models

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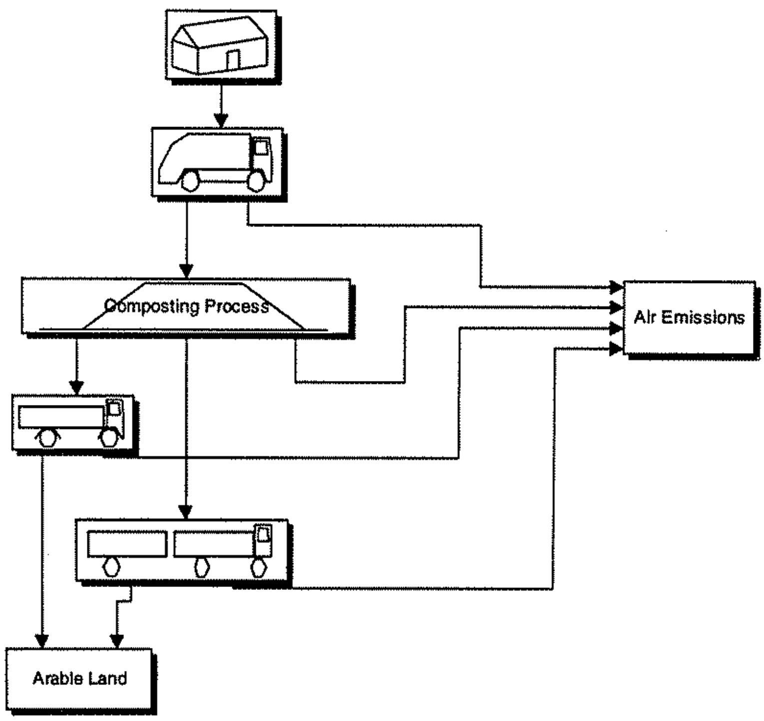

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ABSTRACT

A simulation model, ORWARE, for the handling system for organic waste has been constructed. The purpose of the model is to accomplish a comprehensive view of the environmental effects, plant nutrient utilisation and energy turnover for this large and complex system. The ORWARE model consists of several sub-models; sewage system, incineration, landfill, compost, anaerobic digestion, truck transport, transport by sewers, residue transport and finally spreading of residues on arable land. This thesis is mainly focused on the compost, truck transport and residue transport sub-models, but the entire model is also discussed.

Throughout the ORWARE model, all physical flows are described by the same variable vector, consisting of 43 substances, e.g. carbohydrates, carbon dioxide, dioxins, phosphorus, SO_x, NO_x and heavy metals. This extensive vector facilitates a thorough analysis of the results from an environmental point of view, but involves some difficulties in acquiring relevant data. However, the benefit is that it gives large possibilities for evaluating the outcome thoroughly.

The main conclusions from simulations with the model are;

- There are no alternatives for handling the organic waste that are best in all respects. To find the best alternative, comparisons between different environmentally hazardous emissions, energy use and re-circulation of plant nutrients have to be made.
- To evaluate a large-scale transition towards a more sustainable use of organic waste, i.e. increasing the recirculation of plant nutrients, it is necessary to include both solid and liquid organic waste in the same model.
- An increased recycling of the current waste, containing high levels of contaminants, will increase the environmental load to soil. Presently, a large fraction of these contaminants are put on landfills and thus their environmental effects are delayed for a shorter or longer time.
- The choice of system boundaries is crucial for the results. This implies that the choice of system boundaries in this type of studies have to be clearly defined before the results are evaluated. The impact of chosen system boundaries also has to be discussed after the evaluation.

CONTENTS

List of papers

Paper 1: "The ORWARE model, Part 1, Model Description", Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., Nybrant, T., Sundqvist, J-O., Thyselius, L., Submitted to Journal of Waste Management and Research, October 1996

Paper 2: "The ORWARE model, Part 2, Case Study and Simulation Results" Sonesson, U., Dalemo, M., Mingarini, K., Jönsson, H., Submitted to Journal of Waste Management and Research, October 1996.

Paper 3. The Compost and Transport sub-models in the ORWARE-model - Construction and Data, Sonesson, U., Report 214, Department of Agricultural Engineering, SLU, Uppsala, 1996.

Paper one is a description of the entire ORWARE model, with emphasis on the model structure. Paper two presents a case study of a hypothetical Swedish city, using the entire model for simulations and evaluating the results. Paper three is a presentation of the two sub-models constructed by the author of this thesis, with a presentation of all background data and calculations regarding the sub-models.

1. INTRODUCTION

In the pre-industrialised Swedish society the handling and treatment of organic waste was rather straightforward, either you put the waste on the dunghill or into a local dump. In the first case, the waste was recycled to arable land for food production and in the second case it produced odours for a short time and then was forgotten. The human excreta was returned to arable land via the lavatory, and the urine mainly infiltrated the soil near the dwellings and was lost. When industrialisation started, the same system for waste handling was used in the cities, but the consequences became more severe as the cities grew bigger. The odours from the dumps and even more from the lavatories became unbearable and the hygienic situation was even worse. For example, cholera epidemics were common in Swedish cities during the 19th century.

In order to deal with these problems, technology and transports were introduced in the waste handling and treatment system. Water toilets were introduced and landfills were located outside the towns. At the same time as this development took place, and also as a prerequisite for it, the agricultural sector was offered alternative sources of fertiliser; phosphates from the steel industry, guano and nitrogen fertilisers extracted from the air using large amounts of fossil fuel. Later on incineration was introduced as a means of diminishing the hygienic and odorous problems with solid waste.

In due course, the first problems with this large-scale technological approach appeared, the recipient of waste water becoming damaged, both biologically and with uncleanness. Sewage plants were introduced, first with screens and sedimentation, later with biological reduction of organic matter and with precipitation of phosphorous. Later on, more problems occurred that originated from the waste-handling system, such as dioxins from incineration, leachate and methane from landfills, and emissions from the ever-increasing transports of waste. Nowadays, the problems with the extensive use of fossil fuels have become apparent. Since the mineral fertilisers used in agriculture are produced using large amounts of fossil fuels, the plant nutrients contained in the organic waste again become more interesting, both from an environmental protection point of view and as a means of facilitating sustainable development.

As a result of the above, the organic waste handling system of the future must have a two-fold goal, one is to take care of and treat the waste in a hygienic and environmentally acceptable manner, the other is to recycle the plant nutrients to the food production system. The system largely interacts with other parts of society, e.g. heat- and electricity production, agriculture and, last but not least, the inhabitants in the city. The latter are the producers of organic waste, both in a strict sense but also in the role of source separators and potential sources of contamination of the waste. In Sweden, today, approximately 50% of the solid organic waste is incinerated, 45% is put into a landfill and 5% is biologically treated, mainly composted. Of the sewage water, almost 100% from urban areas is treated in municipal sewage plants.

When analysing such a large system, and a system with numerous interactions between sub-system as well as with other sectors of society, a systematic approach is necessary. To facilitate this, a simulation model has been constructed, ORWARE (ORganic WAste REsearch model). The ORWARE model is intended as a scenario tool. This implies that the main task is to facilitate comparisons of results of simulations of different scenarios, with the possibility to analyse the results on a deeper level, i.e. to discover the sources of every single emission and energy turnover for each sub-model.

The ORWARE model has been developed in the project *Systems analysis of organic waste*, a collaboration project between The Swedish University of Agricultural Sciences (SLU), The Swedish Institute of Agricultural Engineering (JTI), The Swedish Environmental Research Institute (IVL) and The Royal Institute of Technology (KTH), the two former in Uppsala and the two latter in Stockholm. The project has been funded by the Swedish Waste Research Committee, AFR, within the Swedish Environmental Protection Agency. Within this project a case study concerning the city of Uppsala has been performed, which was presented in Nybrant et al. (1996), and another case study concerning a hypothetical Swedish city, presented in paper 2.

Literature review

Biswas (1982) states that modelling using computers is the only way to analyse such complex systems as the waste handling system. The early attempts in this subject were often directed towards the collection of waste; one example is Clark (1978) who describes an optimisation model for waste collecting in Cleveland, USA.

More recent models of waste handling systems are found in Gottinger (1988), Jenkins (1982) and Kaila (1982). They are all examples of economic models that are used to optimise localisation of landfills, incineration plants and transfer stations. Baetz & Neebe (1994), Everett & Modak (1996) and Anex et al. (1996) have mainly followed the same approach, but have included material recycling as one opportunity. None of these models considers environmental or energetic effects.

Chang & Wang (1996) address the problem with the uncertainties the decision-maker faces, by introducing non-exact, or fuzzy, variables in the objective function to be minimised by the model. Huang et al. (1994) presents a input-output analysis of the solid waste handling system, where environmental issues are handled as costs and the model minimises the system with respect to total costs. Gupta & Shepherd (1992) present a model that is based on a database on emissions from different actual plants in USA. Sundberg (1993) has developed an optimisation model for solid waste handling systems, MIMES/WASTE. White et al. (1995) present a Life Cycle Inventory (LCI) concerning municipal solid waste.

MIMES/WASTE has a vector of limited extent for flow characterisation, especially concerning organic pollutants and plant nutrients. On the other hand, MIMES/WASTE considers several waste fractions that are not included in ORWARE. The transport of residual products (as compost) is not included, which may have considerable impact in scenarios with a high degree of recycling plant nutrients. MIMES/WASTE considers the landfill as a sink, i.e., emissions from the landfill are not included in the model. Furthermore, it does not take waste water into account.

White et al. (1995) studied approximately the same substances as in ORWARE, and also largely the same processes, with the exception that they do not include any sewage plant. Hence the waste water is outside the scope of the study, as well as he transport of residues to farm land. The waste included are municipal solid waste, and materials recycling is included. The study is an inventory of the emissions and energy turnover in the system today, but it may also be used for simulating and evaluating different scenarios.

We have not found any model in the literature that can be used to evaluate the environmental effects of introducing a more cyclic system for organic waste. In our model, the waste originating from toilets is included, this is essential when evaluating recycling of plant nutrients, since a major part of all plant nutrients that leave the urban society is found in this waste fraction.

2. METHODS

Systems Analysis and Modelling

Systems Analysis

A system may be almost anything. It is a number of parts combined to a unit. It may be an engine with numerous parts working together to produce power and exhaust gases, a grain field with the soil, plant and weather interacting and producing grain, gases and leachates, it may also be the entire solar system. Practically all systems can be said to be built up of several sub-systems as the atoms are subsystems of the molecule, the trees are subsystems of the forest and our solar system is a sub-system of the Milky Way.

Systems analysis is an approach to analysing any phenomenon in the world, looking at the world as a set of sub-systems making up the whole universe. The system analyser is very aware of this structure and chooses to include only those sub-systems he or she finds belong to the system to be studied. The sub-systems included in the study are said to be inside the *systems boundary*, all others are outside. The choice of system boundaries is one of the most important steps when accomplishing a systems analysis, since the result from the analysis may depend heavily on this choice. When choosing the system boundaries, the basic consideration of the systems analyser is to make a thorough definition of the purpose of the study.

The objective of the study is crucial for the following decisions, it determines the:

- Demand for accuracy of data required,
- Choice of tools that are used in the work
- Assumptions regarding the behaviour of the system
- Time horizons that are to be surveyed in the study

According to Miser & Quade (1995), systems analysis "contains many scientific components, it is not itself a science...it uses methods and knowledge of science insofar as possible and strives to uphold similar traditions. Good practice holds that:

- Results should emerge from processes that can be duplicated by others to obtain the same results.
- Calculations, assumptions, data and judgements should be reported explicitly"

It is not possible to state a detailed scheme for performing a system analysis, the systems under study vary too much, but a summarised sequence is presented in Figure 1. However, the work is very iterative to its nature and there are several exceptions to this scheme:

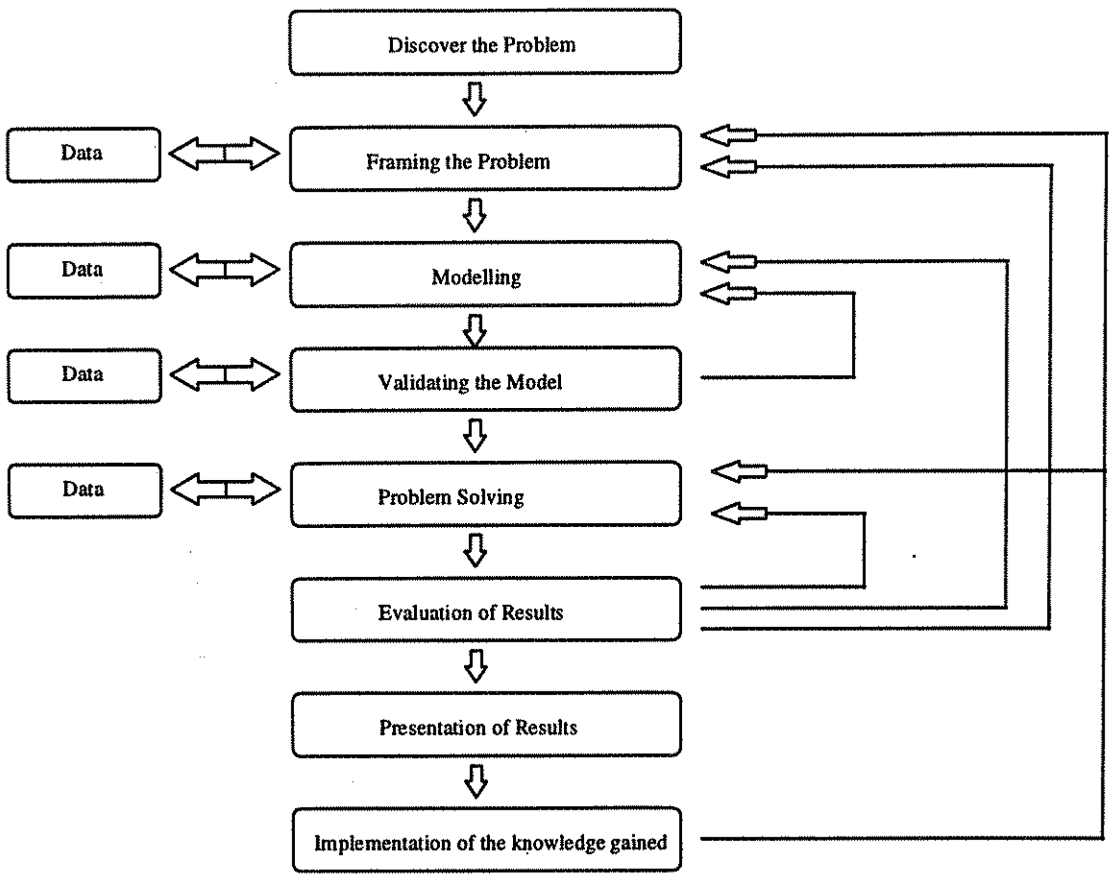

Figure 1. The systems analysis project (Gustavsson et al., 1982)

Models

A model is a more or less formal depiction of some system. Miser & Quade (1995) states that models can be described as:

- Mental
- Verbal
- Physical
- Mathematical

The model described in this report is a mathematical model. This type of model can be described as either (Gustavsson et al., 1995):

- Static or Dynamic
- Continuous in time or discrete in time
- Time determined or action determined
- Deterministic or Stochastic

The type of model you choose for description of your system depends on several factors. The most important one is the purpose of the study. The availability of relevant data also affects the choice, another factor is the knowledge and experience of the modeller.

Systems Analysis and Modelling, ORWARE

Type of model used

As mentioned in the introduction, the system that is to be studied, the system for handling and treating organic waste, is complex and large. This made the choice of using a mathematical model easy, since informal models can not be used to transfer information between different people concerning large systems. They imply great conformity in the way the involved parties apprehend the system and this generally restricts the use of informal models when dealing with large and complex systems.

When the choice is whether to use a static or a dynamic model, the purpose of the study is of importance. If we are interested in the systems behaviour during a relatively short time after some interference or change in the system, a dynamic model is preferred. If we are interested in the steady state the reached by system after some time, the static approach can be used, even if the system is dynamic. A dynamic model demands more accurate knowledge of the structure of the process. Furthermore, Kaila (1987) states that a dynamic model may provide the optimal solution, but does not give an insight into the behaviour of the system as given by a series of simulation experiments with a static model.

Almost all processes in the organic waste handling system have dynamic properties, i.e. the output depends not only on the current input, but also on all previous, or historical, inputs. The data concerning both waste amount and composition are yearly averages, as well as most of the data from actual waste treatment plants. This implies that most indata are yearly averages and the time constants of the processes modelled are much shorter than that. As a result, the models have to be static. Furthermore, as mentioned above, a dynamic model demands detailed knowledge of the structures ruling the process as well as more accurate information. This knowledge is not available for all processes, or parts of processes, included in the model. This together with the fact that ORWARE is intended as a means of studying the result from the average for a year, made the static approach the best alternative.

A stochastic model is used when the behaviour of a system varies in a stochastic manner, and there is a lack of knowledge concerning the mechanisms responsible for these results. A stochastic behaviour of a system can be modelled as a deterministic model if the variations are negligible, or if the aim of the study is to analyse averages over a reasonably long period. ORWARE is a model dealing with average values and therefore there are no stochastic elements included. As a result, the indata, the parameters used, and the results from ORWARE, are averages.

A summary of the formal description of our model states that ORWARE is:

- Formal
- Mathematical
- Static
- Deterministic, using averages as indata and creating averages as results

The first step in a system analysis is to conceptualise and frame the problem. The conceptual model (which can be said to be the picture of problem after it has been "framed", according to the scheme in Fig. 1) is presented in figure 2.

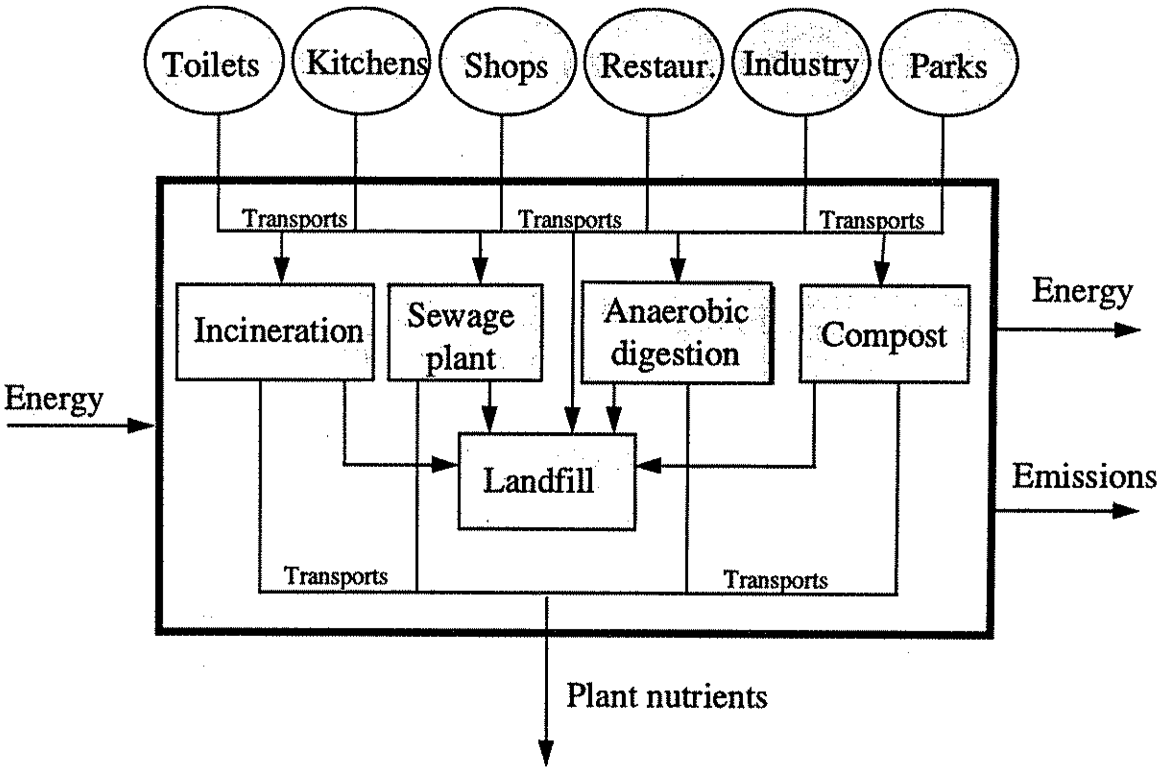

Figure 2. The conceptual model.

This conceptual model was the starting point when constructing the computer model. The aim when modelling was to keep the modular approach, i.e. that each treatment process and transport should be modelled separately to facilitate construction of all kinds of scenarios. This approach required a uniform way of describing the flows of material and emissions, and we chose to address this problem by using the same vector to describe all physical flows modelled.

The vector

In ORWARE, all physical flows between sub-models when they are connected to each other to build up a scenario, are described by the same 43-element vector (Table 1). All physical flows, such as wastes, air emissions, water emissions and residual products, are in the form of "kg of each substance per year". The decision on which substances to include in the vector was based on the substance having at least one of the following characteristics:

- Important for the performance of some sub-model
- Environmentally hazardous
- Valuable in some aspect

Table 1. The vector used for describing physical flows in the ORWARE model

Substance	Reason for inclusion	Substance	Reason for inclusion
Dry Matter (DM)	1	H_2O	1
Volatile Substance (VS)	1	Total nitrogen	1, 2, 3
Total carbon (C-tot)	1	N-NH_3/NH_4^+	1, 2, 3
C-Slowly degradable organics (C-chsd)	1	N-NO_X	2
C-Moderately degradable carbohydrates (C-chmd)	1	N-N_2O	2
C-Rapidly degradable carbohydrates (C-chfd)	1	N-NO_3^-	2, 3
C-Fat	1	Total sulphur	2, 3
C-Protein	1	S-SO_X	2
BOD_7 (Biological Oxygen Demand, during 7 days)	1, 2	Cl-total	2
COD (Chemical Oxygen Demand)	1, 2	P-total	2, 3
CO_2 of biological origin	2	K-total	3
CO_2 of fossil origin	2	Ca-total	3
CO	2	Pb	2
Particles	2	Cu	2, 3
CH_4	2, 3	Cr	2
Organic volatiles (VOC)	2	Ni	2
Halogenated volatiles (CHX)	2	Zn	2
Halogenated organic compounds (AOX)	2	Hg	2
Dioxins	2	Cd	2
PCB	2	Total oxygen	1
Poly-aromatic hydrocarbons (PAH)	2	Total hydrogen	1
Phenols	2		

1= Important for the performance of some sub-model
2= Environmentally hazardous
3= Valuable in some aspect

Sub-models

The ORWARE model consists of several sub-models that are combined to different scenarios by choosing the appropriate sub-models to connect to each other. All sub-models in ORWARE are listed below.

- Sewage plant, described by Dalemo (1996) and in paper 1.
- Incineration, described by Mingarini (1996) and in paper 1.
- Landfill, described by Mingarini (1996) and in paper 1.
- Compost, described in papers 1 and 3.
- Anaerobic digestion, described by Dalemo (1996) and in paper 1.
- Collecting of waste and subsequent transport to some treatment facility, described in papers 1 and 3.
- Transport of residues to agriculture, described in papers 1 and 3.
- Spreading of residues on farm land, described by Dalemo (1996) and in paper 1.

System Boundaries

The system boundaries for the ORWARE model are (see also Fig. 2):

- Collecting and treating of organic waste within a certain geographical area.
- All transports necessary to bring the residues to either farm land or landfill.
- Spreading of residues on arable land, the system boundary is placed "one mm above the soil surface" which implies that only the energy consumption and exhaust gases from the tractor are included, not other emissions from the utilisation of the residues as fertiliser.

This project aimed at working with ***organic wastes*** which, in the project were broadly defined as coming from living organisms. The exact types of wastes that were to be included in the project proved to be difficult to define. Quite clearly, wastes such as human excreta, food wastes, park and garden wastes, etc. should be included. However, the discussion became more difficult when considering, for example, different paper qualities, packages and textiles, especially as these products (wastes) are being produced from a mixture of biological and synthetic materials. A compromise definition was finally adopted, where the goal of an improved recirculation was taken into account, and then this definition was used in a very pragmatic way. In this study, organic wastes were therefore 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.

The wastes included in the project were:

- human urine and faeces and other components of sewage water,
- organic wastes from industry, trade, restaurants and private homes,
- park and garden wastes.

Paper and plastic were only included in the model to the extent that they, as minor components or contaminants, were included in any of the above organic waste fractions.

Accuracy of the results

The accuracy of the results from a model depends on the accuracy of the indata and the structure of the model. That the quality of indata affects the result is obvious; if the indata are an approximation, surely the result becomes an approximation. As mentioned above, ORWARE uses average values as indata and parameters, thus making the result averages.

When constructing a model there are different levels of accuracy of the data and knowledge concerning the phenomenon modelled. This accuracy level is important when judging how general a model is. We will use the following terms to describe different accuracy levels:

- <u>Mechanistic.</u> The mechanisms ruling the phenomenon is known, e.g. stochiometry or geometrical relations
- <u>Empiric.</u> All mechanisms are not known. Relations between indata and results are established using experiments and statistical methods.
- <u>Measurements.</u> The same as empiric, but no statistical relations have been established.
- <u>Plausible assumptions</u>

Throughout the modelling work, we have strived toward the mechanistic or empirical levels. The method of modelling such a large vector implies that the demand for data is large and since positions in the vector can not be empty, we are often forced to use plausible assumptions to complete the parametrisation of a sub-model. This implies that even if the majority of the relations describing a process are well known, some substance have never been investigated, forcing the modeller to make assumptions on that particular substance.

One thing that has been the subject of long discussions within the project group is how the results that stem from processes with such big differences in time should be compared? The emissions from the incineration plant and the transports occur within some seconds, extending from the anaerobic digestion and compost within a few weeks to some months, and finally, from the landfill there may be emissions for ever, i.e. infinite time. The pragmatic decision was that emissions from all processes except the landfill could be compared directly. The landfill is handled as follows; all emissions that occur during the initial period are compared with all other emissions. The initial period, or *surveyable time*, is defined as extending up to the end of the methane phase, this can be estimated to 100 years. The material that is still on the landfill after that time is presented as emissions during the *remaining time*, and can either be regarded as either potential emissions, or material left in the landfill after the surveyable time.

Computer implementation

When modelling the ORWARE model, we have used the software SIMULINK/MATLAB (Math Works Inc., 1993). The basic reason for this was that this language offers a graphical interface to the user which is desirable especially when modelling big systems. Another major reason was that this language has few limitations regarding types of models, complexity, etc. It therefore offers great flexibility and potential for further development in the future. It is also a very well-structured language; the models consists of sub models, in a hierarchical structure. This facilitates a combination of overview of the entire system with detailed modelling of the single processes.

The Compost Model

I have not found any general model for composting in the literature. Practical experiences and explanations of parts of the process are available in the literature, as well as numerous analyses of mature compost. The degradation model has been developed using the above-mentioned knowledge from literature. Three types of composting are modelled in ORWARE:

- Centralised large-scale composting in a reactor.
- Centralised large-scale open-air windrow composting.
- Small-scale composting, either one compost in each dwelling, or in each neighbourhood.

The processes are assumed to be the same, i.e. the final products are the same and also the gases produced as long as the feedstock is the same. In reality, the main difference probably is the reaction rates, provided that good composting practices are used. This implies that the assumption that all three processes are the same can be made, since ORWARE describes an average year.

The differences between the three types of composting are the energy consumption, the possibility to utilise the produced heat, the possibility to clean the exhaust gases and also the costs (Table 2).

Table 2. Differences between the three types of composting facilities

Type of facility	Energy consumption	Utilisation of produced heat	Cleaning of outlet gases	Costs
Home	zero	No	No	low
Windrow	medium	No	No	medium
Reactor	high	optional	Yes	high

The assumptions used in modelling the compost are:

- The water content is suitable, 50%, all the time and the leachate is returned to the compost
- The aeration is sufficient
- The compost is allowed to mature

The structure of the model is described in figure 3. The composting process is modelled in the following way:

Part of the ***organic carbon*** is degraded to CO_2, the remainder is mainly transformed to humus (a small amount, 3%, is carbonised). On an average, between 50 and 70% is degraded but it differs between materials, lignin for example, is not degraded at all, while sugar and starch are degraded to 80%.

Nitrogen can be mineralised to ammonia and perhaps also to N_2O. In the model, the ratio between nitrogen and carbon determines the losses of nitrogen according to a formula from Kirchmann (1985):
N-loss (% of incoming) =0.55903-0.01108*(C/N). The losses are distributed as follows; 2% N_2O, 2% N_2 and the rest is NH_3 (Paper 3).

Heavy metals are not affected by the composting process. The percentages are higher in the mature compost, since the organic matter is degraded to approximately 50% of its mass. The amount of metals, though, is the same as in the feedstock.

Organic pollutants are divided in three streams in the compost block. The first is the percentage that is still left in the mature compost, the other is the part that is degraded during composting and finally there is one part that is gasified during the process. The proportions between these streams differ for each organic pollutant considered in the model.

The compost gas cleaning is modelled as a biofilter, consisting of mature compost, preceded by a condensation with recycling of the condensate to the compost. In this equipment, 90 of the NH_3 and N_2O are absorbed, of which 10% is denitrified to N_2. 50% of the CH_4 is assumed to be oxidised in the filter.

This sub-model is thoroughly described in paper 1 and paper 3.

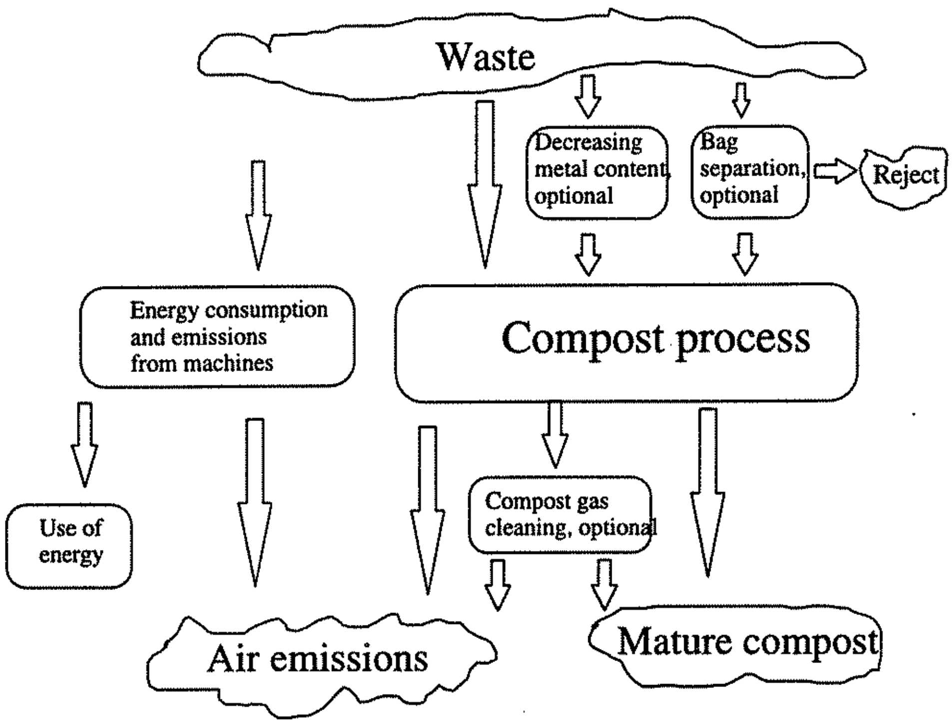

Figure 3. Structure of the compost model (Paper 3).

The transport model

The truck transports are divided into three different categories; garbage truck, ordinary truck and truck and trailer. The garbage truck can be run either in a collecting route or as a main road transport.

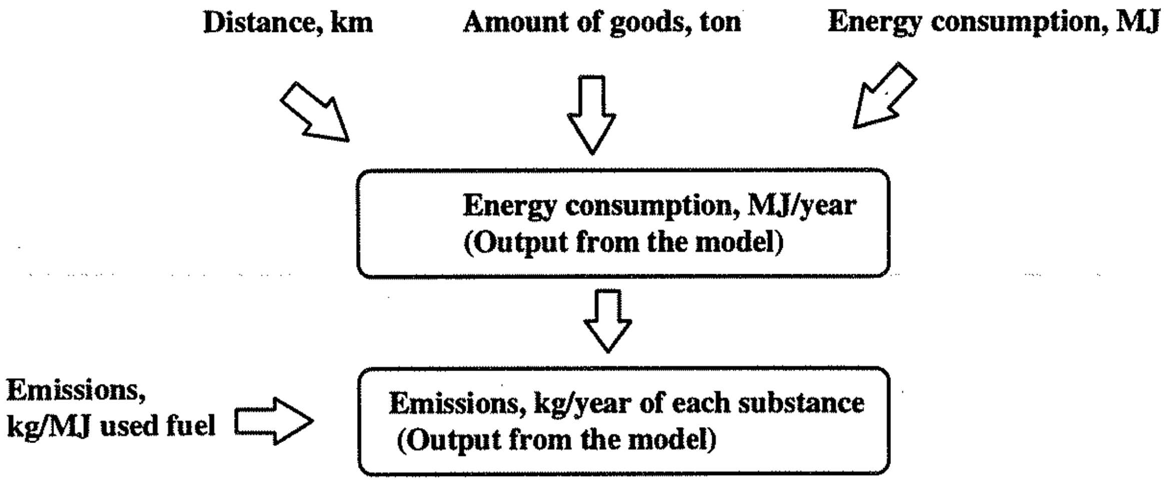

Figure 4 . Structure of the truck transport blocks.

The three transport categories have the following general characteristics:

- Garbage truck. This transport has a high energy consumption. The useful load is rather small, because a large part of the loading capacity is used for the compressing unit and the steel container. Moreover, a significant amount of energy is used for the compressing work itself and the collecting of household waste is, due to its nature, energy-demanding, because of all the stops and accelerations. This makes the energy consumption per ton*km high (8.2 MJ/ton*km). The model is based on low emission vehicles and high quality diesel fuel.
- Ordinary truck. The major part of residual product transports, such as sewage sludge and compost, is performed with ordinary trucks, equipped with a platform. These transports are one-way on main roads. The energy use (MJ/ton*km) is much lower than for garbage trucks since the useful load is higher. However, the emission per MJ is higher because the ordinary trucks are modelled for standard equipped vehicles using standard diesel fuel.
- Truck and trailer. This transport is the most energy-efficient one, due to the high ratio between useful load and total weight. The emission per MJ is the same as for an ordinary truck, but because of the high percentage of the useful load the emissions per ton of transported goods is lower.

The truck transport sub-model is thoroughly described in paper 1 and paper 3.

Table 3. Energy consumption for the different types of transports, including empty return transport

Type of transport	Energy consumption (MJ/ton and km)
Garbage truck collecting route	8.2
Garbage truck, main road transport	4.4
Ordinary truck	1.2
Truck and trailer	0.9

The "transport distances for residues to arable land" model

The transport distance for getting the plant nutrients back to arable land is not fixed, but is calculated during each simulation. The parameters used in this sub-mode is specific for each region. The average distance in the "Case study Uppsala" is calculated with the following presumptions;

- Maximum application rate of nitrogen is 90 kg/ha and year (with such a low application rate almost all crops can utilise the nitrogen without large losses).
- Maximum application rate of phosphorus is 15 kg/ha and year (this application rate corresponds to the average phosphorus content in the harvests around Uppsala).
- The amount of arable land surrounding the city of Uppsala, as ha/km radius, is described by: Arable land=80.6*(radius)^2+3035 (arable land in ha, radius in km) (Paper 3)
- Only 20% of the arable land is available for spreading of residual products.

Each source of "manure" is treated as follows; first the ratio N/P is calculated, if the ratio is higher than 6 (90/15=6, max. application rate of N/max. application rate of P), then nitrogen is dimensioning for the amount to be spread of that specific manure. If N/P is below 6 then P is dimensioning. After that, the acreage need for each manure is calculated and the total acreage is calculated as a sum. The average distance is calculated using the presumptions mentioned above together with data on how much arable land there is within different distances from Uppsala, see Figure 5. This sub-model is thoroughly described in paper 1 and paper 3.

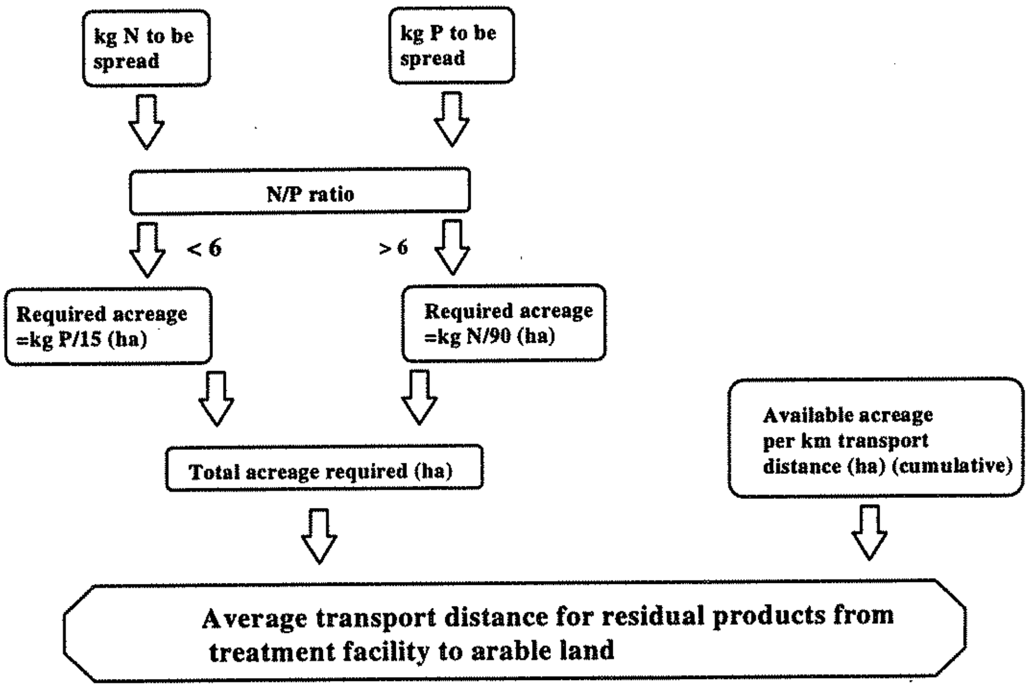

Figure 5. Structure of the transport distance calculating block (Paper 3).

3. EVALUATION OF RESULTS

Background

Simulations with ORWARE produces large quantities of data. First there are the main results, the systems total emissions to air and water, the material ending up on arable land and landfills, respectively, and finally the systems energy turnover. Since each of them is represented by the 43-element vector, the simulation result is somewhat incomprehensible. Furthermore, when analysing the results from a scenario, it is necessary to partition the total emissions according to its origin. For example, which source contributes most to the emission of HCl, or which waste is the main source of cadmium to arable land? This procedure, together with the fact that several scenarios are simulated in order to compare them, makes the evaluation very difficult using every single substance on its own.

One way to deal with this problem is to put the results, both energy and emissions, as bars side by side, thus making a visual profile of every scenario. This gives a better overview of the results, but still it is very difficult to accomplish accurate analyses.

We have chosen another approach, that is to use methods developed in Life Cycle Assessment (LCA).

Life Cycle Assessment - Approach

To make the evaluation of the resulting emissions more comprehensible, we have used a method that has been developed within LCA. This method enables grouping of substances with the same type of impact on the environment, as for example CO_2 and CH_4 in the group of substances that may cause global warming. The different substances have different weighting factors according to the potential effects they have in the environment. The effect categories used in the case study presented in paper 2 are:

- Global warming (measured as CO_2-equivalents)
- Photochemical oxidants formation, due to organic substances (ethene-equivalents)
- Photochemical oxidants formation, due to NO_X
- Eutrophication (O_2- equivalents)
- Acidification (H^+-equivalents)
- Health effect (kg contaminated bodyweight, calculated as the amount of pollutant divided by the LD-50 value for that pollutant)
- Resource depletion, this category is dealt with to some extent, i.e. use of oil and flows of phosphorus and potassium.

We have not considered such categories as noise, risk of accidents, "habitat alterations and impacts on biological diversity", "human health - impact on working environment", "resource depletion - water and land", or "depletion of stratospheric ozone". The reason for excluding these was mainly that our model does not handle the information needed to evaluate these categories, and in some cases there was also a lack of reliable weighting factors. The weighting factors used and a more thorough presentation of the reasoning are presented in Nybrant et al. (1996).

Another method from LCA that may be used when evaluating the results, is the use of "functional units". A functional unit can be explained as a "utility" provided by the system. This concept is related to system boundaries mentioned above but is not equal. The use of these units transforms the results concerning energy turnover and plant nutrient utilisation to emissions, thus making the result more coherent, but it also makes the result less transparent. If the concept of functional units is to be used, or if only the first unit, handling and treating of a certain amount of organic waste, is to prefer, depends mainly on the objective of the study.

The functional units used in Nybrant et al (1996) were:

- Handling and treating of a certain amount of organic waste
- Spreading a certain amount of nitrogen on arable land
- Spreading a certain amount of phosphorous on arable land
- Producing a certain amount of heat
- Producing a certain amount of electricity

The first unit is clearly the one that determines the geographical boundaries for the system, furthermore it is the "base unit" which will be fulfilled in all scenarios. The remaining two units are dealt with as follows:

1. After simulation of all scenarios, the scenario that produces the largest amount of utility is identified.
2. In the other scenarios, where there is a lack of the utility at hand, there is a complementary addition with the emissions and energy use that are used for producing the utility in some other technical system.

The recycling of plant nutrients to arable land may serve as an example; one scenario produces very little of the utility "Spreading a certain amount of nitrogen on arable land" compared with the scenario that produces a large amount of that utility. Figures on emissions and energy consumption for producing the differing amounts of nitrogen as mineral fertiliser are added to that scenario's other emissions and energy turnover, thus facilitating a more "fair" comparison between the two scenarios.

Case Studies

The entire ORWARE model has been used in two case studies, the first was performed when constructing the model and concerns the city of Uppsala. This study is presented in Nybrant et al. (1996). The second study concerns a hypothetical, medium-sized, Swedish city and is presented in paper 2. This latter case study consists of comparing five scenarios:

- **Scenario 1,** The solid organic waste was incinerated and the waste water was treated in a conventional sewage plant. This scenario was an image of one of the two common situations in Sweden today.
- **Scenario 2,** The solid organic waste was landfilled and the waste water was treated in an conventional sewage plant. This is the other common situation in Sweden today.
- **Scenario 3,** The solid organic waste was source-separated and treated in an anaerobic digester and the waste water was treated in a conventional sewage plant.
- **Scenario 4,** The solid organic waste was source-separated and treated in a central composting plant with exhaust gas cleaning equipment. The waste water was treated in a conventional sewage plant. The composting of all waste made addition of straw necessary and the extra transports needed were included in the system.
- **Scenario 5,** This was a slight variation of scenario 1, the only difference was that the urine was source separated and spread directly on arable land

For all scenarios the following assumptions were made: All sewage sludge, compost and sludge from anaerobic digestion was spread on arable land. In figure 6 the ORWARE model set for scenario 3 is presented.

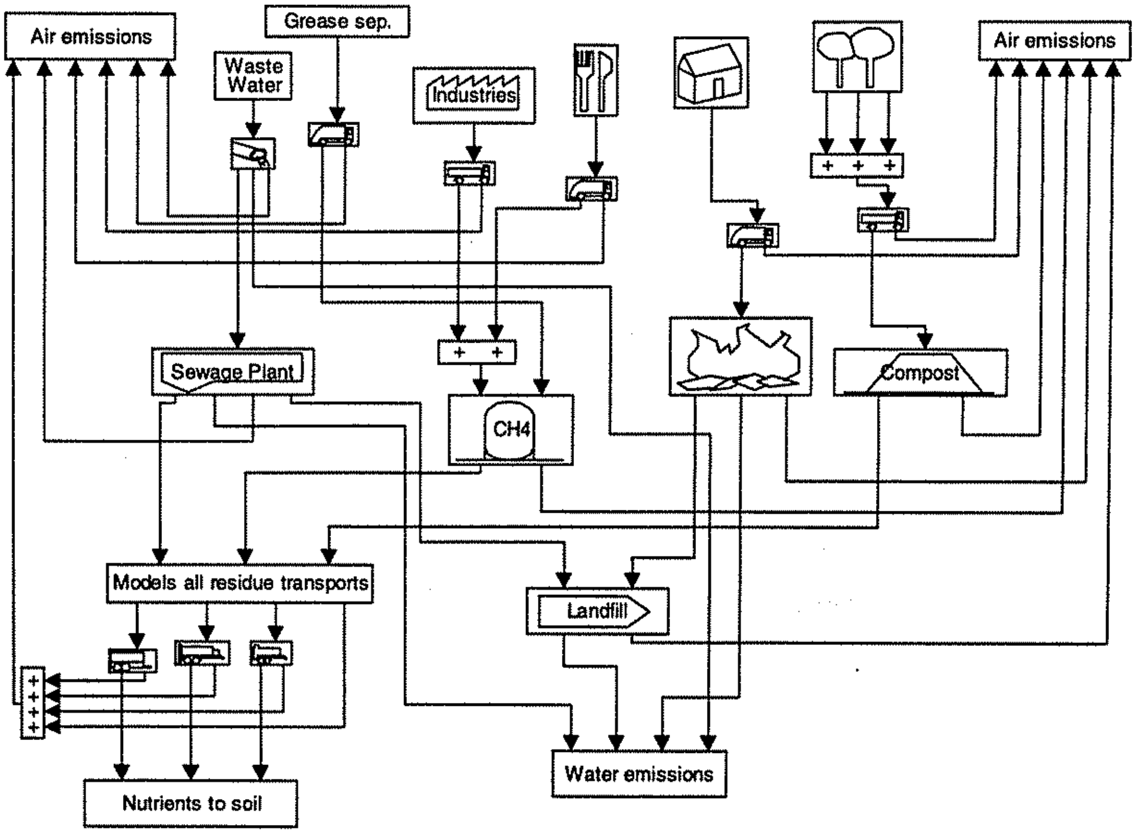

Figure 6. The ORWARE model for scenario 3 in paper 2

Results and discussion from the case studies

The compilation of the results is presented in figure 7. The emissions were grouped according to the procedure described previously. The adjustments made because of different production of utilities in the system as described earlier, are not included in this study, since the main objective was to test the ORWARE models applicability.

There was no obvious "best" scenario, even when we only looked at the environmental effects. However, without ranking the different categories, the compost scenario seems to have the lowest impact for most environmental effects. Another positive aspect of this scenario was the relatively high recirculation of nitrogen. The drawbacks were mainly the poor energy balance, which, if functional units had been used, could have altered the outcome regarding the emissions.

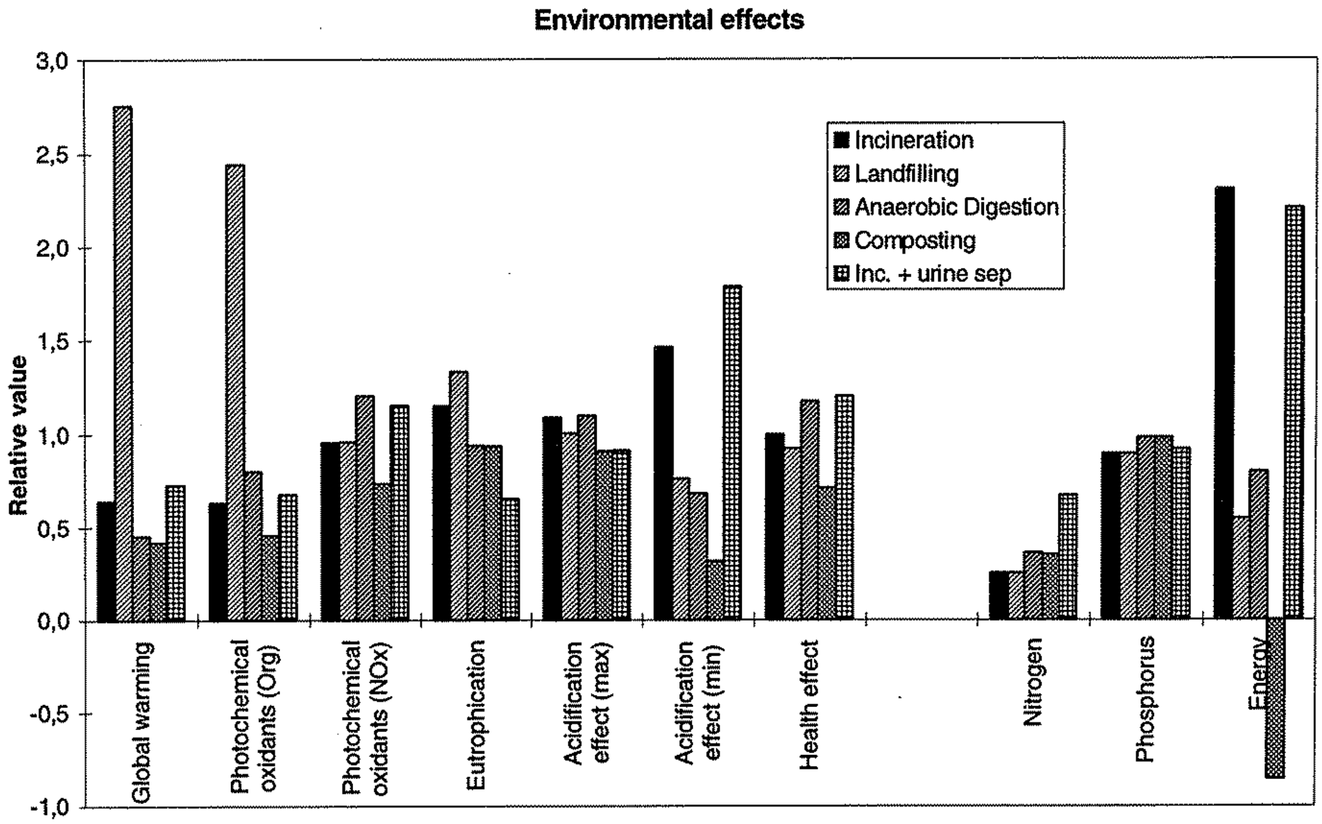

Figure 7. The results from the case study, evaluated using LCA-methodology. Relative values, i.e. the mean value for each category, are calculated and the value for each scenario is related to that average.

The incineration scenario had the greatest energy surplus but also the poorest (together with the landfill scenario) recirculation rates for plant nutrients. Furthermore, the energy produced was heat, which may be considered as an energy form of lower value. The scenario also affects the acidification and eutrophication to a relatively great extent.

The landfill scenario did not seem to be the best in any respect, even if the emissions that occur after the surveyable time were not included in Figure 7.

The results for the anaerobic digestion scenario showed a good energy balance, but rather high emissions of all effect categories in which NO_X is included. This is explained by the choice of using the produced methane in a stationary engine for producing electricity and heat, the engine not being equipped with any catalytic exhaust cleaner. If we had chosen to use the methane for producing heat only, in a gas boiler, the NO_X emissions would have decreased.

Introducing urine separation increases the return of nitrogen dramatically, this is because the sewage plant used for this fraction only recovers approximately 30% of the incoming nitrogen in the sludge.

One conclusion from this case study could be that a scenario that it would be interesting to study a scenario that combines composting and urine separation. A compensation of the differences in the utilities provided by the system in the different scenarios, i.e. using the functional unit approach, is essential to compare the different scenarios. The results from the simulations and the evaluations are presented in detail in paper 2.

4. CONCLUSIONS

Applicability of the ORWARE model

The ORWARE model has proved to be a useful tool when investigating the large and complex system that makes up the handling and treating of organic waste. The main advantages are:

- The possibility to get an overview of the whole system's behaviour when simulating different scenarios, combined with the possibility to analyse every emission down to the deepest level, i.e. every emission of a single substance can easily be traced to its source.
- The modularity of the model, which facilitates construction of scenarios in a pedagogical acceptable way, as well as it makes changes in the sub-models and construction of new sub-models easy to accomplish.
- The large vector of substances, which facilitates covering of most environmentally hazardous compounds found in waste and a very flexible evaluation of the results.

The major drawbacks are

- The lack of "user-friendliness", which may be a hindrance for fellow researchers and practicians to utilise the model.
- The lack of systems to secure.
- The system boundary that states "organic" waste is to some extent artificial, the border does not exist in reality.

General conclusions

The ORWARE model is found to be very useful, as stated above. Some other major findings and conclusions are:

- The model is intended for comparing different scenarios.
- The model can not provide the whole answer to any question, the result from it must be seen as a part of the basis of decision.
- Since the system for waste handling interacts so intensively with other technical systems, the choice of replacement fuels for producing heat and electricity as well as choice of emission factors for mineral fertilisers may heavily affect the results of the study. The user of the model must be very aware of this.
- The interaction with humans in society is not included. This must be kept in mind, since a system that seems to be the best in all respects, but places great demands on the inhabitants, might fail if implemented in society.

Future work

The transport models have to be improved in order to give them a more general application, both regarding collection of household waste and transports of residues to arable land. As it is today, the model for collecting waste may only be used in urban areas and for the A to B transport the same load is always assumed. The transport distance for residues to arable land must be improved since this transport is very important for scenarios with a high degree of plant nutrient recirculation. This may well be done using a "Geographical Information System" (GIS).

The compost model may be improved concerning the nitrogen turnover and emissions of gaseous nitrogen compounds. The fate of organic pollutants should also be improved if more data were found.

The limitation regarding waste types may well be changed, i.e. including other waste types would widen the scope and applicability of the model.

A comparison between effect categories may be involved, this may be done in co-operation with researchers in the field of LCA.

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