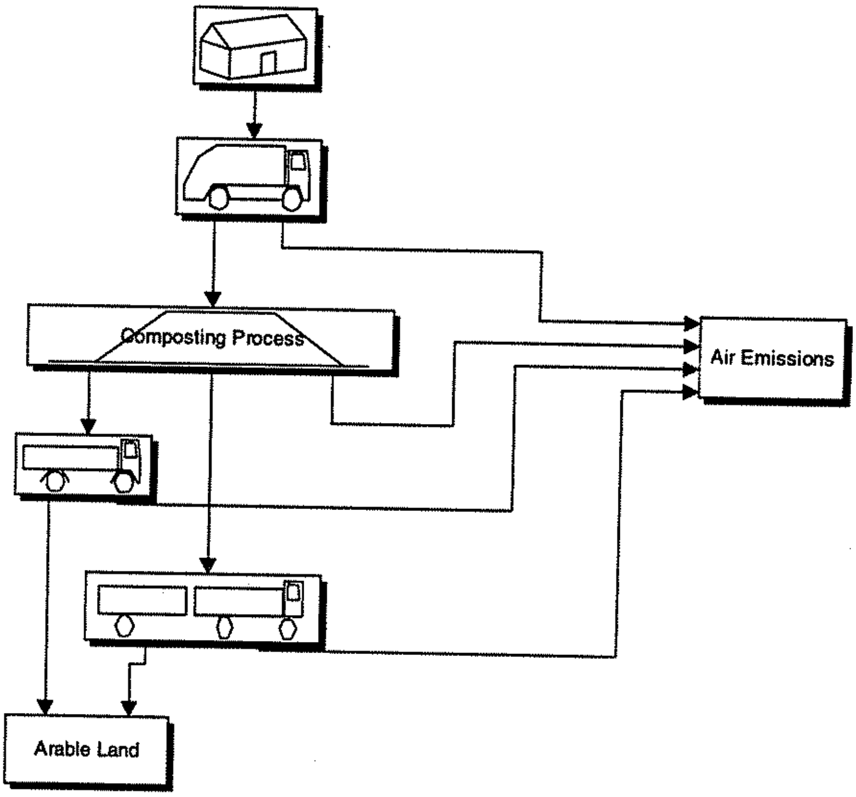
MODELLING OF THE COMPOST AND TRANSPORT PROCESS IN THE ORWARE SIMULATION MODEL



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ABSTRACT

The system for handling and treatment of organic waste is very large and complex, especially in urban areas. It consists of numerous transports, different treatments and different use of residual products. This system also interacts with several other technical systems in society, e.g., district heating, handling of other wastes and material for re-use, and agriculture as a receiver of residues. The complexity of the system under study makes a systematic approach necessary to get the appropriate overview, which has led to the construction of the simulation model ORWARE (Organic Waste Research). This model is intended as a means of analysing the environmental impact, use of resources, and energy turnover of the handling system for organic waste.

The model consists of treatment facilities for waste in the system as well as all the transports necessary for collecting the waste and transport residual products to landfills or arable land. ORWARE is modular, all sub-models can be connected to each other. The sub-models developed are:

- Sewage plant
- Incineration
- Landfill
- Composting
- Anaerobic digestion
- Transports
- Spreading of residues on arable land

ORWARE is used as a scenario tool, the scenarios that are to be studied are constructed by connecting the sub-models needed to represent the scenario and a simulation is performed. An analysis of a region consists of simulation of several scenarios and then evaluation mainly of the differences between the results. The results from the model are:

- Air emissions from the entire system
- Water emissions from the entire system
- Energy turnover for the entire system
- Amount of plant nutrients and contaminants recycled to arable land

These total emissions can also, in the analysis of the results, be presented as emission/energy turnover/plant nutrient recycled, from every single source. One way of making the results easier to analyse, is to use Life Cycle Assessment methodology to group the emissions into several environmental effect categories, and this is what have been done in the case studies performed.

In this report, the modelling of, and indata to, the ”compost model”, the ”transport model” and the ”Transport Distances for Residual Products to Arable land model” are presented. The models are static and the results from a simulation depend only on the flow of material into the models. The model works with a variable vector consisting of 43 elements. In that vector, substances with an environmental effect, substances that affect some process, and substances that are valuable as plant nutrients are included.

1. INTRODUCTION

During the last five to ten years there has been a debate in society about waste handling. The subject has become a symbol for the "recycling society" and "sustainable development". There have been numerous arguments about whether it is wise to source-separate the household waste in one organic, "compostable" fraction or not. The arguments in the debate were sometimes not comparable; the ones advocating incineration of the waste stated that it was a waste of good energy to compost the organic waste, whereas the opponents said that incineration entailed much transportation work and that composting was a local solution and a good way to utilise the plant nutrients in the waste. In 1990, legislation was introduced that prohibited landfilling or incineration of "mixed household" waste. In the debate there were also spokesmen for anaerobic digestion, which utilises both plant nutrients and the major part of the energy embodied in the waste. Other solutions as "biocells" on the landfills were also advocated. From an agronomic point of view, the content of plant nutrients in the organic waste was crucial when deciding on what measures to take, and since the major part of the nutrients is found in sewage, it seemed necessary to include that in the discussion as well.

It was in this context that the research project "Systems Analysis of Organic Waste" (Nybrant et al., 1996) was started, as a means of providing a systematic approach to the above-mentioned problem. One of the first things that was discovered was an understanding that the system for handling organic waste interacts intensively with other systems in society. One was the district heating, as mentioned above, and the collecting, transport and treatment of other waste fractions and also the behaviour of the inhabitants who are the producers and also potential contaminators of organic waste. Another very important sector when evaluating the organic waste handling system is the agricultural sector, including the fertiliser industry, since one of the major gains when recycling organic waste is that it can replace mineral fertilisers. Mineral fertilisers are manufactured using either limited resources (P and K fertilisers) or large amounts of fossil fuels (N fertilisers). When the waste is anaerobically degraded, as in an anaerobic digester or in a landfill, methane is formed, which can be used to replace diesel fuel for transports, or oil for co-generation of electricity and heat.

In the above-mentioned project, the simulation model ORWARE (ORganic WAste REsearch) was constructed. This model facilitates simulation of different scenarios of the waste handling system, thus supplies an overview of the whole system's emissions and energy turnover, as well as the plant nutrient recycling.

The processes included in ORWARE are:

- Sewage plant
- Incineration
- Landfill
- Compost
- Anaerobic digestion
- Collecting of waste and subsequent transport to some treatment facility
- Transport of residues to agriculture
- Spreading of residues on farm land

When performing a simulation, the following indata are required:

- Amount and composition of all organic waste produced within the region studied
- Geographical data on where the waste is produced, where the treatment facilities are located, and also the amount of arable land that is available in the region, as well as knowledge of the accessible road network.

The outputs from a simulation are:

- Total air emissions from the system, with each source and substance separately presented.
- Total water emissions from the system, with each source and substance separately presented.
- Total amount of residual products recycled to arable land from the system, with each source and substance separately presented. This is one measure of the economising of scarce resources, as phosphorous and potassium.
- Total energy turnover, the amounts and energy form from each sub-model are presented.

The emissions may be grouped together according to some concept, environmental effect categories as in Life Cycle Assessment (LCA), for example, to simplify the analysis of the result. However, the results can be traced back to both source (compost, waste transport etc.) and substance (CO_2, CH_4 etc.). This facilitates thorough analysis of each scenario and provides a base for good understanding of the system's behaviour.

This report presents the ”Compost model”, the ”Transport model” and a transport sub-model called ”Transport Distances for Residual Products to Arable land”. The other sub-models are described in Mingarini (1996) and Dalemo (1996). The ORWARE model has been developed in the project *Systems analysis of organic waste*, a collaboration project between the Swedish University of Agricultural Sciences, The Swedish Institute of Agricultural Engineering, The Swedish Environmental Research Institute and The Royal Institute of Technology. The project has been funded by the Swedish Waste Research Council, AFR. Within this project a case study concerning the city of Uppsala has been performed, which is presented in Nybrant et al. (1996).

Methods

The conceptual model that was the starting point of the project is presented in Figure 1. From this structured picture of a part of reality, the computer model was constructed.

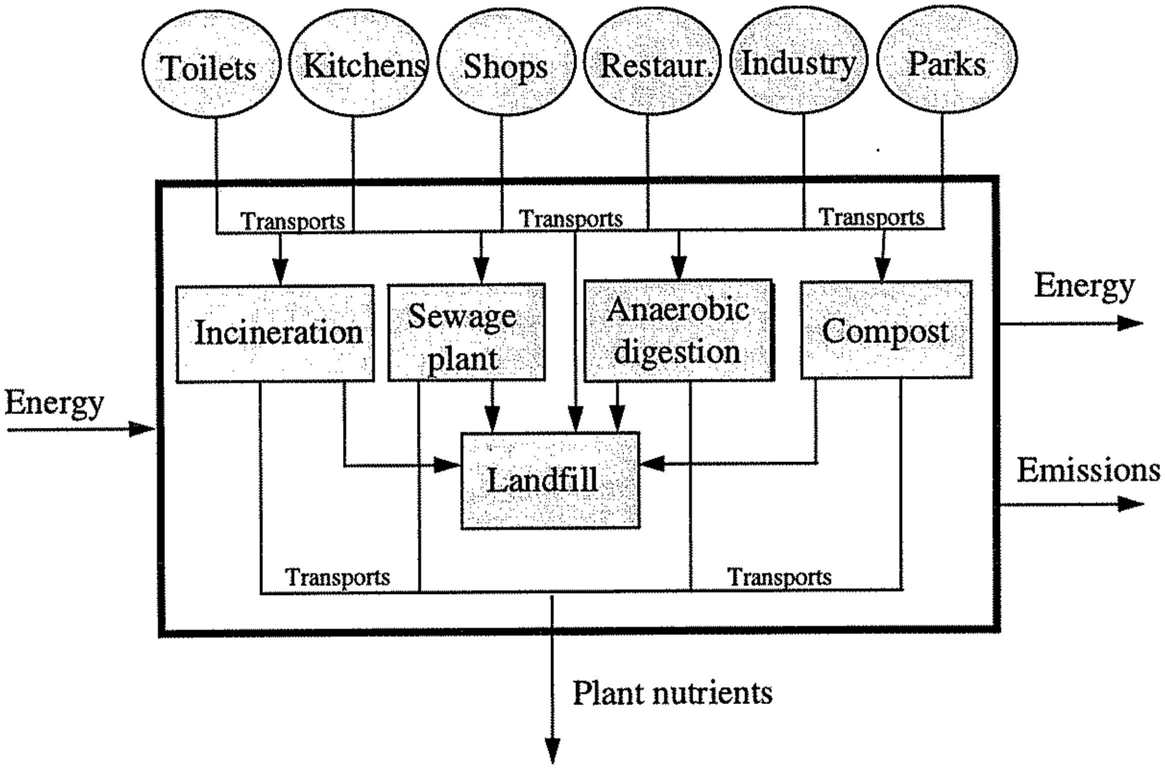

Figure 1. The conceptual model.

The model is strictly modular, which means that the computer model has separate blocks for each sub-model, just as the conceptual model. These separate blocks can be combined in any way to construct the scenarios that are to be studied. However, there is no handbook on how to connect all sub-models, so the construction of scenarios demands detailed knowledge of each sub-model.

All sub-models used in ORWARE have the same basic structure. They have an inflow of waste or residual product, the model calculates the emissions, to air and sometimes to water, caused by the process, as well as the outflow that consists of the residual products. Furthermore, the energy turnover, partitioned in electricity, oil and heat, is calculated. In the transport model the "residual product" is the same as the inflow, since the transport itself does not affect the load, and the model only calculates the energy consumption and the emissions due to combustion of diesel fuel. All indata to the models described in this report form a datafile, where it is easy to check, change and save them.

I have developed the simulation models described in this report by using literature data and consulting waste treatment professionals. The models are linear and static. The main reason for choosing a static approach is that available data on waste generation and emissions from actual plants are yearly averages which preclude a dynamic modelling approach. Furthermore, the system under study is so complex, and dynamic modelling demands more accurate knowledge of the internal structures of the processes modelled. Hence, it was considered unrealistic to construct a dynamic model.

The aim of building these models has been to quantitatively describe reality, in order to observe the outflows, as well as the emissions, when the system layout varies. All physical flows between all sub-models use the same format, a vector, that consists of 43 variables (Table 1).

Table 1. The vector used throughout the ORWARE model

No.	Abbreviations	Reasons for inclusion	Remarks
1	C-tot	1	Total carbon
2	C-chsd	1	Carbon in slowly degradable organics, i.e. lignin etc.
3	C-chfd	1	Carbon in rapidly biodegradable carbohydrates, i.e. sugars, starch
4	C-fat	1	Carbon in fat
5	C-protein	1	Carbon in protein
6	BOD_7	1,2	Biological Oxygen Demand during 7 days
7	VS	1	Volatile Solids (equals DM minus ash)
8	DM	1	Dry Matter
9	CO_2-f	2	Carbon dioxide of fossil origin
10	CO_2-b	2	Carbon dioxide of biological origin
11	CH_4	2,3	Methane
12	VOC	2	Volatile Organic Compounds, for example methane, solvents
13	CHX	2	Halogenated hydrocarbons
14	AOX	2	Adsorbable Organic Halogens
15	PAH	2	Polyaromatic hydrocarbons
16	CO	2	Carbon monoxide
17	Phenols	2	Phenols
18	PCB	2	Polychlorinated biphenyls
19	Dioxins	2	Dioxins, TCDD equivalents, measured according to Eadon
20	O-tot	1	Total oxygen content (in solid material only)
21	H-tot	1	Total hydrogen content (in solid material only)
22	H_2O	1	Water
23	N-tot	1,2,3	Total nitrogen
24	N-NH_3/NH_4^+	1,2,3	Nitrogen in ammonia and/or ammonium
25	N-NOx	2	Nitrogen in nitrogen oxides
26	N-NO_3^-	2,3	Nitrogen in nitrate
27	N-N_2O	2	Nitrogen in nitrous oxide
28	S-tot	2,3	Total sulphur
29	S-SOx	2	Sulphur in sulphur oxides
30	P	2,3	Phosphorus
31	Cl	2	Chlorine
32	K	3	Potassium
33	Ca	3	Calcium
34	Pb	2	Lead
35	Cd	2	Cadmium
36	Hg	2	Mercury
37	Cu	2	Copper
38	Cr	2	Chromium
39	Ni	2	Nickel
40	Zn	2	Zinc
41	C-chmd	1	Carbon in moderately degradable carbohydrates, i.e. cellulose etc.
42	Particles	2	Particles in gas and suspended solids in water
43	COD	1,2	Chemical Oxygen Demand

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

Modelling

When modelling the compost process, the transports and the "transport distances for residual products to arable land", my intention was to use the following method:

- Search in the literature and become acquainted with the subject,
- Use that common knowledge and understanding of the process to construct a basic model, with a structure that corresponds to reality with a resolution that is on the same level as the rest of the ORWARE model.
- Search for numerical data, analyses of composts and feedstock, mass-balances etc. For the transport model, data were found in test reports on exhausts from different heavy vehicles, and additional data were acquired from several personal communications.
- These data are then used when the models are parameterised.
- Finally more data are gathered that are independent of earlier used data and used to verify the models, i.e. perform simulations, and compare the simulation result with these new data.

The process described above is not totally sequential, you often step back as you learn more about the process when collecting data. Construction of a model is largely an iterative process.

In practice, however, it was not always possible to use this method, for different reasons. The major difficulty has been to find enough relevant data. Regarding several substances in the vector I have only found one investigation on its fate during a compost process and other substances have never been analysed in connection with composts or waste. According to the verification of the compost model, it has largely been a matter of judging whether the output from the model was reasonable concerning for example C/N ratio and mineralised nitrogen. In these judgements, personal communications with experienced researchers and also practitioners have been used.

Concerning the transport model, the amount of data on emissions of the substances that are subject to legal restrictions was not the major obstacle. The problem was to find a structure on the model, whereby it could be generalised. The fuel consumption and emissions vary widely depending on the traffic situation and the kind of transport involved. The validation of this model was also a matter of judging whether the outputs were reasonable.

Finally, the "Transport Distances for Residual Products to Arable land" model is largely a matter of collecting and structuring geographical data on the region surrounding the studied area.

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2. THE COMPOST MODEL

There are several compost models described in the literature, some examples are Haug (1993), Person & Shayya (1993), van Lier et al. (1994) and Stombaugh & Nokes (1994). These models are constructed with different purposes compared to ORWARE. They are designed to assist in compost design rather than environmental evaluation. They also often have a narrower validity range, concerning feedstock and/or handling regime. Furthermore, they do not predict the gaseous emissions only as a function of the material that is composted, but also as a function of aeration, temperature etc. No compost model found in the literature models such a large amount of substances as the ORWARE model. In the ORWARE model, the compost sub-model has to use indata according to the ORWARE vector to predict gaseous emissions, composition of the mature compost as well as energy consumption for the whole compost plant. The model must present reliable output with different feedstocks. These are the reasons why it was not possible to use any existing model in the project.

Composting is a process where organisms, mainly micro-organisms such as bacteria and fungi, degrade organic matter under predominantly aerobic conditions. The gaseous degradation products are mainly carbon dioxide (CO_2) and ammonia (NH_3) but small amounts of, for example, nitrogen gas (N_2) are produced. The mature compost consists largely of humus-like substances and some mineralised nitrogen, both ammonium (NH_4^+) and nitrate (NO_3^-). On a micro-scale, though, the conditions often are shifting between anaerobic and aerobic, causing degradation products from anaerobic degradation such as methane (CH_4) and also nitrous oxide (N_2O) which may occur during such shifting conditions.

There are several compost systems used in practice. These can be divided into two main principles, in-vessel (or reactor-) composting with mechanical mixing and/or forced ventilation and open air composting (windrows for example) where mixing and aeration are performed with mobile mixing machinery, sometimes with forced aeration. Composting systems may also be divided using the size aspect. There are large-scale systems, such as those mentioned above, and small scale systems, home- or "back yard" composting. The latter is often in-vessel composting, but without mechanical mixing.

Solid state composting is a batch process, even though composting in a rotating drum gives the impression of a continuous flow process. In practice, however, the material that is fed at one time will predominantly stick together, and the microbiological processes will continue in the same sequence as in a static reactor or in a compost windrow. This implies that the model ought to be constructed in the same way for all different types of composts modelled.

In ORWARE there are three types of composting modelled. The three types are; home composting, windrow composting and reactor (rotating drum) composting. As mentioned earlier, there are no fundamental microbiological differences between them, the basic processes can be considered to be the same. In reality, with the same feedstock and good management of the composts, the gaseous emissions as well as the mature compost will be similar in all three cases, even though the time the degradation process will take differs.

The differences between the three sub-models are the energy consumption for handling the compost, the different possibilities to have exhaust gas cleaning, and the fact that in small-scale home composting systems there are lower percentages of heavy metals (Widén, 1993). The principal differences are explained in Table 2.

Table 2. The three types of composts modelled and the differences between them

	Energy consumption by machinery	Exhaust gas cleaning	Lower metal content, due to better sorting
Home compost	Zero	No	Yes
Windrow compost	Medium	Optional	No
Reactor compost	High	Optional	No

In addition to table 2, there are other differences such as costs and how much transportation that is needed with different systems. These effects are not mentioned in Table 2, because they are not included in the modelling of the compost, they are considered when simulating the whole system with ORWARE and evaluating the results.

Structure of the model

The flow through the compost model may pass one, two or three steps, depending on what composting system that is chosen:

- In the first step plastic bags are removed (along with some organic waste that stick to the bags) and in the case of home composting the heavy metal content is decreased. This first step is used only when the waste is packed in plastic bags or home composting is used.
- Secondly, the compost process is modelled, all calculations concerning the degradation process, which gives the gaseous emissions as well as the composition of the mature compost are performed in parallel. For a majority of substances, the model divides the incoming flow in two outflows, one to gas emission and one to mature compost, using constants. Nevertheless, there are some substances for which the performance of the process depends on connections between different substances in the waste.
- Thirdly, the compost gas cleaning device may be used. Along a parallel line, energy consumption for handling the compost is calculated as a function of the amount of waste being treated. Furthermore, in this part of the model, the emissions from tractors and other machines used during the composting is calculated. The basic structure is presented in Figure 2.

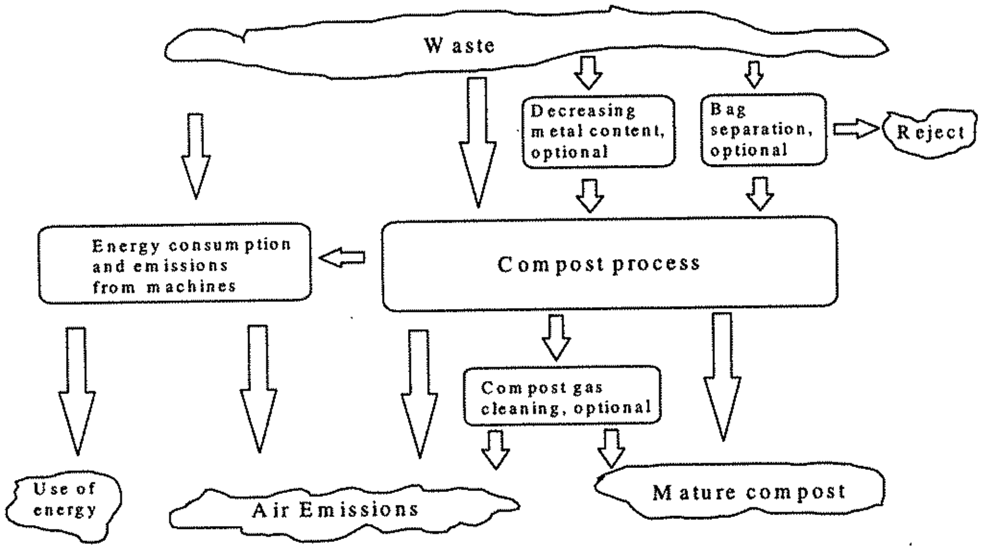

Figure 2. Structure of the compost model in ORWARE.

In the model's computer interface, there are four different entrances, one for home composting one for windrow composting, one for reactor composting and one that is used when the waste is packed in plastic bags. The latter is the case with household waste only and after that pre-processing the waste is directed to either windrow- or reactor compost. Furthermore, there are three parallel composting processes which facilitate modelling the effect of the three management systems (Fig. 3). The model has five exits, one for mature compost from windrow composting, one from reactor composting (including nitrogen trapped in the compost gas cleaning device, the biofilter), one from home composting, one for air emissions, and finally one for the rejects from bag separation and screening. The uppermost level of the compost model as it was set in the Uppsala case study (Nybrant et al., 1996) is shown in Figure 3.

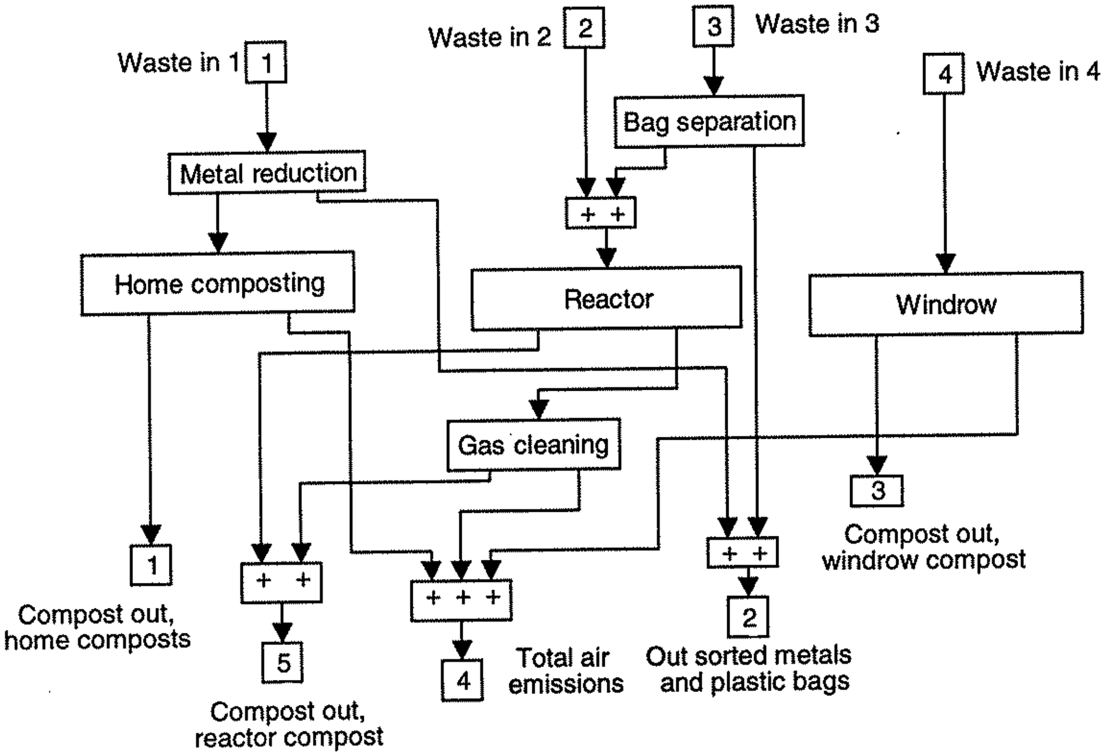

Figure 3. The highest level of the compost model in ORWARE

Lower metal content due to better source separation

The content of heavy metals in home composts is significantly lower than in compost from central facilities (Widén, 1993). This is probably a result of people sorting their waste more thoroughly when they know that the end product is going to be used in their own garden. Since all analyses found on source separated household waste originate from large, centralised systems, it was necessary to model this lower content of metal content to get valid results for home composting systems, the figures used in this sub-model are presented in Table 3.

Table 3. Content of the heavy metals in household waste in home composting systems compared to content in large-scale systems (Widén, 1993)

Metal	Household waste, central compost (mg/kg DM)	Househ. and park waste, 50/50 mix, central compost, (mg/kg DM)	Home compost (mg/kg DM)	Reduction in model when composted at home (%) [a]
Pb	151	103	13.5	90
Cd	1.4	0.88	0.22	80
Hg	0.31	0.40	0.05	85
Cu	202	159	36.5	80
Cr	28	31	20	30
Ni	23	21	8.9	60
Zn	347	297	167	50

[a] The last column is calculated as follows: (Column 3/(mean value of column 1 and 2)). This is because the home compost most likely is a mix of garden- and kitchen waste.

The flow of heavy metals in the "decreasing metal content block", is described in Figure 4. The two-thirds of the metals sorted out that leave the system are explained by better use of battery collecting systems.

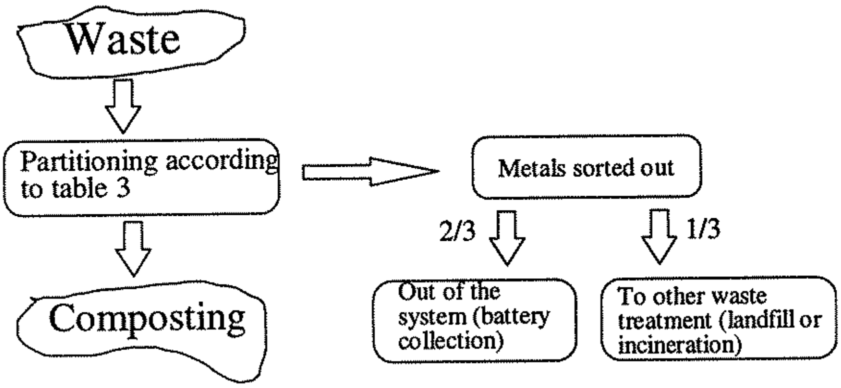

Figure 4. Flow of heavy metals in the "metal reduction sub model"

Bag separation

When the waste is packed in plastic bags it is necessary to remove the bags before composting, otherwise there is a great risk that anaerobic conditions will occur inside the bags. This bag separation is accomplished with a combined cutting and screening machine. The bags are first cut and then the mixture of waste and torn bags is tumbled and blown so the plastic is separated. Along with the bags, there is also some organic waste that is separated. According to Jonsson (pers. comm. 1994), approximately 25% of the organic waste ends up together with the plastic bags. This waste is incinerated or put on a landfill.

Degradation of organic matter

Organic matter is degraded in the compost process. Heat, CO_2, and some methane are released and the mature compost consists mainly of humus-like substances. Different substances decompose to different degrees and with different proportions turning into humus and gaseous C-compounds (CO_2 and CH_4). Proteins also emit different nitrogen compounds such as NH_3 and N_2O during degradation. In Table 4, figures on the carbon part of the material that decompose are presented. In the ORWARE vector, humus is considered as slowly degraded organics (chsd). A more thorough description is found in Appendix 1.

Table 4. Decomposition degree in compost for different nutritives (See also Appendix 1)

Substance	% that turns into CO_2	% that turns into humus
C-chsd (Lignin)	30	70
C-chmd (Cellulose)	90	5 [a]
C-chfd (Starch, sugar)	80	20
C-fat	60	40
C-Protein	65	35

[a] *After composting there is a small residue of undegraded cellulose, in ORWARE this is assumed to be 5% of incoming chmd*

The fate of the nitrogen contained in proteins is discussed below. The major part of the nitrogen left in the compost is organically bound, in humus, the rest is either NO_3^- or NH_4^+. One theory states that under ideal conditions, all mineralised nitrogen occurs as NO_3^-. Actually the ratio between NO_3^- and NH_4^+ is sometimes used as a measure whether the compost is mature or not. Unfortunately, the conditions are seldom ideal and in practice there is always some NH_4^+ present.

The figures used for the N-compounds are :

- $N\text{-}NH_4^+$=1% of N-tot that remains in the mature compost.
- $N\text{-}NO_3^-$=6% of N-tot that remains in the mature compost.

The rest is found in organic form in humus. The calculations behind these statements are presented in appendix 1.

N-losses

The gaseous losses of nitrogen may be considerable. I have used a formula from Kirchmann (1985) that describes the nitrogen losses as a function of the C/N ratio:

N-loss(% of incoming)=0.55903-0.01108*(C/N)

This formula is empirical and is based on trials on manure, straw, green plants and other agricultural products. This formula describes the nitrogen losses from a compost in general. According to von Rheinbaben (1994) the aeration rate is of great importance for the nitrogen losses, the more air that is blown through the compost, the more nitrogen is lost. Hansen et al. (1991) describe experiments with composting of poultry manure mixed with corncobs. Three different temperatures (45, 50 and 60°C) and two aeration regimes (one-way direction flow and reversed direction flow) were studied. The composting time was fourteen days, and since both
von Rheinbaben (1994) and Nakasaki et al. (1993) report that the major part of the nitrogen loss occurs during the intensive first phase of the composting, the results can be used to

compare with Kirchmann's formula. Since the feedstock had a C/N ratio of approximately 20, the N-loss according to Kirchmann's formula should be 33.7% of the incoming amount, or actually somewhat lower since the formula predicts the total losses and the experiments only discuss the losses during the first fortnight. In the experiments mentioned (Hansen et al., 1991), the losses during the first fortnight varied between 21.7% and 30.3%. These results can be considered to correspond well with Kirchmann's formula, which predicts a 33.4% loss over the whole composting time.

Hellmann (1995) measured emissions of N_2O, CO_2 and CH_4 from three compost windrows with different turning regime, daily, every third day and weekly. The windrows were rather small. The emission of N_2O during the first intensive phase was 0.7% of total N-loss on average for the three windrows. During the maturing phase, where no turning were performed, the total amount of N_2O losses was 2.2 times the losses during the intensive phase. Altogether this means 2.2% of lost nitrogen is lost as N_2O. The material Hellman (1995) used was a mixture of 40% household waste and 60% yard waste. This mixture should have a C/N ratio of approximately 45, which according to Kirchmann's formula would give an N-loss of 6% of the nitrogen found in the feedstock, and the measured loss was 9.5% of initial N during 52 days of composting, on average for the three heaps.

Kirchmann & Witter (1989) present an improved formula of nitrogen losses as a function of the C/N ratio where the nitrogen fraction is divided in two parts, one rapidly degraded and one slowly degraded. Unfortunately, this knowledge cannot be used in our model since the vector does not include more than one kind of organic nitrogen compound.

I have used this formula (Kirchmann, 1985) since it describes the nitrogen loss as a function of the C/N ratio and both C and N are part of the ORWARE vector, moreover, it seems logical that the more nitrogen there is in the waste, the more is lost.

The losses are distributed as follows; 2% is lost as N_2O (Hellman reports 2.2%), 2% as N_2 and the rest as NH_3. These last two figures are assumptions based on discussions with Kirchmann (pers. comm. 1994).

Modelling of the other substances

- Incoming VS is not used for calculating the outgoing VS. The outgoing value of VS is calculated as the sum of Chsd and Chmd, the other components of VS are considered to be negligible.
- We assume that the amount of ash increases during composting. This is due to carbonisation and the outgoing amount is assumed to be 103% of incoming. Kirchmann (pers. comm, 1994) mentions between 0 to 12% increase because of carbonisation. Since VS is defined as DM-Ash we get: $DM_{out}=(DM_{in}-VS_{in})*1.03+VS_{out}$
- CH_4 is formed under anaerobic conditions. However, even with good composting conditions CH_4 formation may occur. This is because on a micro level there are always some anaerobic spots where methane is formed. In the model, the amount formed is set to be 0.35% of the CO_2 formed, which is the average methane production in three well aerated windrow composts according to Hellmann (1995) (described above in connection with the part dealing with gaseous N-losses).
- The amount of oxygen and hydrogen is calculated from the amount of C-chsd and C-chmd. Data on the percentage of O and H in these substances are presented in Sonesson & Jönsson (1995).

- We assume that the moisture content is 50% (wet base) in the mature compost, this makes the content of H_2O equivalent to the amount of DM.
- The organic compounds in the ORWARE vector (VOC, CHX, AOX, Phenols, PCB and dioxins) are modelled as follows; the incoming amount is divided into three outflows, by use of constants. This assumption is made mainly because we have found very little data on these processes. The values of the constants are presented in Table 5. The background is presented in appendix 1.

In Table 5 a summary of the figures and relations stated above is presented.

The heavy metals pass through the compost without changes in the amounts, the same applies for P, K, S and Cl.

Table 5. Constants used for substances affected by the compost process in the compost model

Substance	Mature compost	Gaseous emission	Degraded in the process
VS	chmd+chsd		
DM	$(DM_{in}-VS_{in})*1.03+VS_{out}$		
CH_4		0.35% of CO_2 formed	
O-Tot	Calculated as percentage of outgoing chsd and chmd		
H-Tot	d:o		
H_2O	equals DM in mature compost		
VOC (% of incoming)	1	74	25
CHX (% of incoming)	1	74	25
AOX (% of incoming)	100	0	0
PAH (% of incoming)	82	0	18
Phenols (% of incoming)	3	0	97
PCB (% of incoming)	60	20	20
Dioxin (% of incoming)	100	0	0

Compost gas cleaning

The compost gas cleaning equipment is used together with the reactor or windrow compost. A condensation step from which the condense liquid is returned to the compost process is followed by a biofilter, consisting of mature compost through which the outlet air passes. The material in the filter is supposed to be used as the rest of the compost, i.e., the nitrogen captured in the filter is also returned to the mature compost.

Of the ammonia in the outlet air, 70% is found in the condensation liquid (Norin, 1996). According to the same reference, the remaining ammonia is captured in a biofilter consisting of peat. Witter & Kirchmann (1989) found that 100% of the ammonia in the outlet air was captured in a peat filter for the first nine days and thereafter the leakage increased. Norin (1996) mentions a similar behaviour of the peat filter, the filter's cleaning efficiency decreases after some time. The nitrogen that is caught in the biofilter is either denitrified and leaves the filter as N_2, or immobilised and remains in the filter material in organic form, e.g. humus or microbes. Norin (1996) found that 50% of the nitrogen caught in the peat filter remains in organic form and 50% is denitrified. Since the filter modelled is not a peat filter, I use somewhat lower figures, see Table 6. I assume that N_2O has the same behaviour as ammonia. Of the formed CH4, 50% is assumed to be oxidised to CO2.

Table 6. Figures used in the compost gas cleaning model

Substance	Percentage that remains in the mature compost (i.e. caught in the filter)	Percentage that passes the filter in its initial form (CH4, NH_3 or N_2O)	Percentage that passes the filter as N_2
N-NH_3	80	10	10
N-N_2O	80	10	10
CH_4	50 [a]	50	

[a] *This CH_4 is oxidised to CO_2*

Energy consumption

The energy taken into account is the diesel fuel and electricity used when handling the composts. Since no manual labour is considered, this implies that the home composting uses no energy. I have used the average of the two references, and the proportions of electricity and diesel fuel are assumed to be as the proportion reported by Hovsenius (1987). The figures used in the model are presented in Table 7.

Table 7. Energy use for the different compost types (kJ/kg waste treated)

Type of compost	Use of electricity (Hovsenius, 1987)	Use of diesel fuel (Hovsenius,1987)	Total use of energy (Savage et al., 1991)	Chosen values	
				Elect.	Diesel
Reactor	81.6	4.3	118.8	97	5
Windrow	4.8	35.4	84.8	7	55

Emissions from diesel engines

The emissions from the vehicle used at the composting facilities are the same as in the "spreading block" (Dalemo, 1996) concerning CO, VOC and NO_X. The rest are the same as in the "transport block, A to B transport, ordinary truck", from the chapter ”The transport model”, later in this report.

Discussion

Validity range

In a strict sense, the validity range is very narrow for this type of model, the reason being that most relations regarding the degrading process are dynamic and non-linear, and the model uses static and linear relations that are valid under only the very circumstances these relations were stated. Since there are no investigations on these dynamic and non-linear relations, I have to extrapolate linear relations and make some assumptions to get the compost model to work within the ORWARE model.

However, since the assumptions made for the model are the common rules for how a large-scale composting plant should be managed, the utility of the model is good for the purposes of the ORWARE model, i.e. to study the whole system's behaviour under normal working conditions.

The way I have verified the model is by simulating composting of;

- Source-separated household waste
- Park waste

The results of these simulations are found in Appendix 3. The resulting output vectors are evaluated in the sense of searching in the literature for analyses on some of the substances in the ORWARE vector and see if the results seem to be reasonable. My conclusion is that for the above-mentioned waste fractions the emissions of NH_3, CH_4, N_2O and CO_2, as well as the content of humus and mineralised nitrogen in the mature compost presented by the model are reliable.

The conditions for which the compost model is valid are presented below.

- All composts will in due time be mature, in practice this means that the mineralised nitrogen occurs mainly as nitrate and not ammonium, all fat, protein and chfd is totally decomposed, while some chmd and chsd remains in the material.
- The composts are well managed, i.e. there are no failures that give rise to high emissions of methane and other products of unsuitable composting conditions, i.e. they are turned and wetted etc. when needed.
- All leachate water is collected and returned to the compost.
- The feedstock contains both nitrogen and carbon. Concerning C/N-ratio the model has been tested between 22 to 66 (C/N ratios for source-separated household waste and park waste, respectively).
- Feedstock that are too dry will be wetted to a suitable moisture content.
- The feedstock has a DM content above 35% of wet weight.
- The feedstock are grind to the extent that are common in compost facilities under working conditions.

Concerning the organic pollutants, VOC, CHX, AOX, PAH, PCB, phenols and dioxins, there is a need for more research, the data used is from one investigation only or assumptions, so concerning these substances the model's validity is very limited and the assumptions have been conservative. However, in the evaluation of the results presented in Nybrant et al. (1996), the organic pollutants mentioned above did not have a large impact on the overall outcome of the simulations. Therefore, the behaviour of the organic pollutants in the compost do not seem to be crucial for the environmental impact of the process.

Future improvement

The calculations on energy use must be more accurate. More data on the turnover of nitrogen in the compost are required in order to more precisely model the nitrogen losses. These nitrogen emissions (NH_3 and N_2O) are of great importance both for the environmental impact of the compost and also for the recirculation of plant nutrients, since these emissions represent nitrogen losses from the system. Purely for environmental protection reasons, emissions of CH_4 could be more precisely modelled. In correspondence, the compost gas cleaning facility ought to be improved.

It would be desirable if the fate of the organic pollutants could be modelled more precisely, but that requires more data and investigations that are outside the scope of the project and also beyond the competence of our project group.

In general, all new data found in the literature and concerning the ORWARE vector will be included in the model, but there is no intention of working actively with this in the forthcoming project.

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3. THE TRANSPORT MODEL

If the handling and treatment system for organic waste is changed, the need for transports will also change. If more residual products are to be brought to arable land the transport demand will increase. Since one of the purposes of the ORWARE model is to evaluate what the environmental effects and energy turnover will be if the organic waste handling system is changed, the transport model is of importance to get accurate analyses of the change in the system.

Transport of waste has been subject to several investigations found in the literature. The reason for this is that this part of the waste handling system stands for approximately 60-80% of the total costs involved in the handling system for solid waste in Sweden. As a result, all models I have found have an economic approach, for example Gelders & Cattrysse (1991), who describe a linear programming method to make waste collecting in Brussels more efficient. Vasanthakumar Bhat (1996) developed a simulation model to direct the garbage trucks to different landfills (or other treatment facilities) in order to minimise the total waiting time for the trucks.

Since the purpose of the transport sub-models in ORWARE is to calculate the emissions and fuel consumption, the optimisation approach found in the above-mentioned articles could not be used, new models had to be developed.

The transport sub-model is divided into three different blocks, "Garbage truck", "Ordinary truck" and "Truck and trailer". They are organised in the same way, it is parameters that differ. Furthermore, the "Garbage truck" block can be used both in a "collecting route" and an "A to B" transport while the other two can only be used in the "A to B transport". Altogether, this makes four different types of transport situations.

Structure of the model

The amount of energy used is calculated from data on energy consumption per ton and km (MJ/ton*km) together with data on the weight of the goods (ton) and the distance (km). This energy consumption is an output in itself but it is also used when calculating the emissions from the transports. Emissions from trucks are strongly related to the amount of energy that is used by the truck, therefore the emissions are calculated as kg/MJ used diesel. The structure of the models is presented in Figure 5.

The energy consumption per ton*km (MJ/ton*km) and the emissions per MJ (kg/MJ) are data that vary with the type of transport. The amount (ton) and distance (km) are data that depend on the studied case, they differ from one scenario to another.

I have only taken into account the emissions that occur due to combustion of diesel fuel, the emissions from tyres, lubricating oil, etc. are not included. Another important note is that when we mention distances it is the actual number of kilometres the waste is transported that is the measure. This means that for the "A to B" transports it is the one-way distance and for the "collecting route" it is the whole distance. However, in the "A to B" transports, the empty return transport is included in the model.

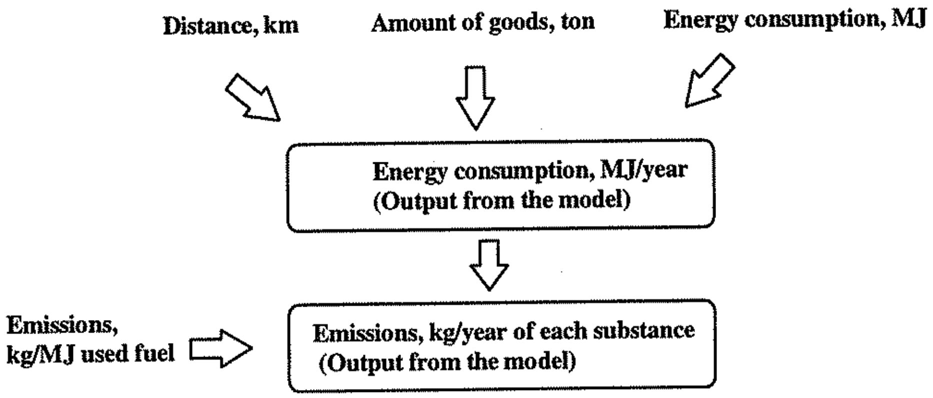

Figure 5. Structure of the transport blocks in ORWARE.

Garbage truck, emissions and energy consumption

This block describes a transport where waste is collected from several places (e.g. households and restaurants), small amounts from each place. The driving plan assumed is; first a transport, with the truck empty, from the garage or treatment facility to the collecting area, then a linear loading during collecting until the truck is full or the working day is finished and finally a transport to the treatment facility. This leads to the conclusion that the average load (load factor) during collecting of waste is 50% of maximum load, one way empty, one way full and between those two a linear loading. Further on, I will refer to this transport work as a "collecting route". This model is only valid is for simulating collecting of waste in urban areas.

If the waste is to be transported to some treatment facility outside town (for example, a central compost or landfill) there is a main road transport added which is less energy intense than that mentioned above. This transport work is further on referred to as "A to B transport with garbage truck".

Energy consumption, Collecting route

The calculation of the energy consumption is presented below. All data are averages and are according to the drivers at Uppsala Public Service Works (1994).

- Average load is 3.3 tons.
- Driving distance for collecting and taking the garbage to the incineration plant is 32 km/day.
- The amount of waste collected is 2.4 loads/day, 3.3 ton/load gives 7.9 ton/day.
- This gives the performance that is 128 ton*km/day.
- Fuel consumption is 24.5 kg/day, equals 1057 MJ/day.
- All together this makes the energy consumption for the collecting route **8.2 MJ/ton*km.**

Emissions, Collecting route

The data presented is mainly from Grägg (1992). The tests in that study were performed with a Volvo bus equipped with the same engine as the garbage trucks in Uppsala. The difference is that this vehicle was equipped with an ordinary exhaust emission control. In order to correct this (the garbage trucks in Uppsala are fitted with a so called "city filter), see Appendix 2.

The emissions were measured using the so called "Bus cycle" (Braunschweig cyclus). This means that the test simulates an average bus tour in an urban area, with many stops and accelerations and rather low average speed. This test also uses the entire vehicle tested on a "rolling road" where the power is measured on the driving wheel. The emissions used in the model are presented in Table 8.

*Table 8. Emissions and energy consumption for the transport models (g/MJ used diesel fuel and MJ/ton*km, respectively) (Appendix 2)*

Emission or energy consumption	Garbage truck, Collecting route	Garbage truck, A to B transport	Ordinary truck (1) and truck and trailer (2)
Energy consumption	8.2	4.4	1.2 (1) 0.9 (2)
C-tot	20.30	20.20	20.30
CO_2-a	74.00	74.00	74.00
CH_4	$1.00*10^{-3}$ [a]	$1.00*10^{-3}$ [d]	$1.00*10^{-3}$
VOC	$35.00*10^{-3}$	$28.00*10^{-3}$	$66.00*10^{-3}$
PAH	$1.74*10^{-6}$	$1.50*10^{-6}$	$2.50*10^{-6}$
CO	0.15	0.06	0.29
N-tot	0.42	0.43	0.53
N-NO_X	0.42	0.42	0.53
N-N_2O	$2.60*10^{-3}$ [b]	$2.60*10^{-3}$ [d]	$2.60*10^{-3}$
S-tot	0.02 [c]	0.02 [d]	0.09
S-SO_X	0.02 [c]	0.02 [d]	0.09
Particles	$9.00*10^{-3}$	$8.20*10^{-3}$	0.01

[a] *Almén (1992) states 0.13 mg/MJ, Brandberg (1992) states 5 mg/MJ (LCA-concept)*

[b] *Calculated from Almén (1992)*

[c] *The emissions of SO_X are calculated as follows; According to Jersin (1993) diesel fuel of environmental class 1 (EC1) is only allowed to contain 20% of the sulphur content of EC2, I assume that the same goes for the SO_X content, i.e. I take 20% of the measured value for "ordinary truck"*

[d] *Same value as for the collecting route*

Energy consumption, A to B transport with garbage truck

The fuel consumption for a garbage truck described above is approximately 0.21 kg/km with maximum load and 0.13 kg/km empty (Upplands Motor AB, 1994). Performing A to B transports, the assumed situation is that the vehicle is full one way and empty the other. This makes the average fuel consumption 0.17 kg/km. This fuel consumption corresponds well with results presented in Hammarström & Karlsson (1987). The energy consumption is calculated as follows; the total distance (including empty return transport) is used to calculate the fuel consumption as MJ/trip using data on the average fuel consumption. The maximum load and the one-way distance is used to calculate the transport work performed. With the same maximum load as for the collecting route and the fuel consumption presented above, we get **4.4 MJ/ton*km**, which is the figure used in the model (Table 8).

Emissions, A to B transport with garbage truck

As in the case of the collecting route, the data for emissions from the A to B transport with garbage truck are mainly from Grägg (1990) and Grägg (1992). The difference is that the emission data are taken not from the test according to the "bus cycle" but from a "mode 13 test". This means that the simulated driving scheme consists of 13 different loads with different duration. This test simulates "countryside driving". The power is measured on the engine and not on the driving wheel. The emissions for this model are presented in Table 8.

Ordinary truck, emissions and energy consumption

This transport mode describes an ordinary truck, equipped either with a platform or some other simple kind of addition. The driving scheme is assumed to be as follows; The truck is loaded with a maximum load at "A", emptied at "B" and driven empty back to "A". The transport distance is A to B, the return distance is not to be added since the energy consumption for that part is included in the one-way distance. Examples of this transport type are sewage sludge from the sewage works to farmland and industrial waste transported to the landfill. I have assumed only main road transport.

Energy consumption

The fuel consumption is the same as for the garbage truck concerning kg/km, i.e. 0.17 kg/km on average. The maximum load though, is 12 tons which gives **1.2 MJ/ton*km** (Table 8).

Emissions

The data are mainly from Egebäck & Hedbom (1991). The measuring was made in a "mode 13 test". The engines had power ratings between 152 and 331 kW and were turbo-charged. The tested vehicles had normal engines without exhaust gas cleaning. The figures are mean values of 28 tested vehicles. The CO_2 content is from Grägg (1992), this figure is also a mode 13 test but on two vehicles only. The SO_X content is from IVA (1990) where the ratio between NO_X/SO_X is given. This, combined with data on NO_X from Egebäck & Hedbom (1991), gives the figures on SO_X. The efficiency, measured on the driving wheels, is 37%. The emissions for this model are presented in Table 8.

Truck and trailer, emissions and energy consumption

This transport is the most energy efficient type, because of the high ratio between useful load and vehicle weight, combined with the fact that only main road transports are performed. An example of a transport with truck and trailer is ashes from the incineration plant to the landfill.

Energy consumption

The energy consumption is calculated using the following data; The maximum load is 30 tons, the fuel consumption is 0.42 kg/km when loaded and 0.21 kg/km when empty (Upplands Motor AB, 1994). This gives an average fuel consumption of 0.315 kg/km. This fuel consumption corresponds well with results presented in Hammarström & Karlsson (1987). The energy consumption is calculated as follows; the total distance (including empty return transport) is used to calculate the fuel consumption as MJ/trip using data on the average fuel consumption (the load factor is 50%), the maximum load and the one-way distance is used to calculate the transport work performed. With the maximum load and fuel consumption presented above we get **0.9 MJ/ton*km**, which is the figure used in the model (Table 8).

Emissions

The emission from this transport block is assumed to be the same as for the "ordinary truck block".

Discussion

Validity range and Utility

The transport model is constructed using mainly statistical data on waste collection vehicles operating in the city of Uppsala. This implies that the model is valid only under these circumstances. In practice, however, the model will present reasonably good data when used in similar driving situations and that is the case for most medium-sized Swedish cities. Eriksson et al. (1995) presents figures for fuel consumption from Gothenburg, 128 MJ/ton collected waste which corresponds well with my figure 134 MJ/ton, assuming 25 km driving distance for collecting. If the model is used to simulate waste collecting in rural areas the inaccuracy in the output will increase as the area studied get less dense populated. Used in large cities, the model may present results that are misleading due to the longer hauling distances from housing areas to treatment facilities, and also perhaps due to different traffic situations.

The A to B transports are valid for simulating countryside driving and as models of trucks with the same maximum weight and load capacity as the trucks modelled.

Future improvement

Collecting waste with a compacting truck is very fuel consuming, on a litre-per-km basis. The reason for this is that a lot of work performed by the vehicle does not depend on the driving distance, e.g. compacting the waste, lifting waste bins and all stops and accelerations. In the garbage truck model, these facts are not taken into account, the fuel consumption only depends on the distance driven. A model that considers differences concerning driving situations and includes loading and compacting work would probably increase the utility of the collecting sub-model. This ought to be implemented in order to facilitate simulations of more widely differing kinds of areas, both with higher and lower population density.

The A to B transports ought to be adjusted in order to facilitate simulation of town traffic as well as other truck sizes and load capacities.

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4. TRANSPORT DISTANCES FOR RESIDUES TO ARABLE LAND

The average distance needed for transporting residual products containing plant nutrients varies not only with the amount but also with the composition of the residual products. This implies that it is not possible to state a distance before the simulation. The way we have solved this is to construct a sub-model as an integrated part of the ORWARE model that calculates the actual distance for the transport during the simulation. I have found only one article in the literature that deals with a similar problem, i.e. Nilsson (1995) who calculated the transport work required to supply two straw-fired heating plants with fuel from the surrounding farmland. Our problem is the principally the same, the difference is that in our case the trucks are empty on the way from the farms.

Structure of the sub model

To make the calculation of transport distance it is necessary to relate the distance to some data found in the ORWARE vector, the relevant figures are the amounts of nitrogen and phosphorus. Knowledge of the available acreage of arable land within certain distances from where the waste is treated is also needed. This data is in the form "hectare available per km transport distance". This last function is an equation of the second degree.

The amount of nutrient (N or P) per hectare will determine how many hectares that are needed to spread the waste. Together with data on "hectares available per km transport distance" it will give the mean transport distance.

The figures used below are from the Uppsala case study (Nybrant et al., 1996). We have presumed that the maximum dose of nitrogen is 90 kg/ha and year and for phosphorus it is 15 kg/ha and year. This makes the N/P-ratio 90/15=6. This ratio determines which of the two nutrients that is dimensioning. The model calculates this ratio for each residual product. It then groups together all residual products where N is dimensioning and, after that, forms another group of residual products where P is dimensioning. Thereafter, the acreage needed for each of the two groups is calculated, the total acreage needed is the sum of the acreage needed for these two groups. Finally, the average distance is calculated from the figure of acreage need in hectares and ”hectares available per km transport distance”. This calculation scheme is presented in Figure 6. When the average distance is calculated, all residual products are assumed to be transported that distance with an ordinary truck, as previously described in this report.

In practice, for residual products that are considered as phosphorus fertilisers, a five-year yield is spread at one time and subsequently there is no P-nutrient spread at all for five years. However, when it comes to calculating the distance, there is no need to take this into account, as in a five-year period the differences in transport distance will even out. In the "spreading block", on the other hand, this fact is considered when calculating the energy consumption for spreading.

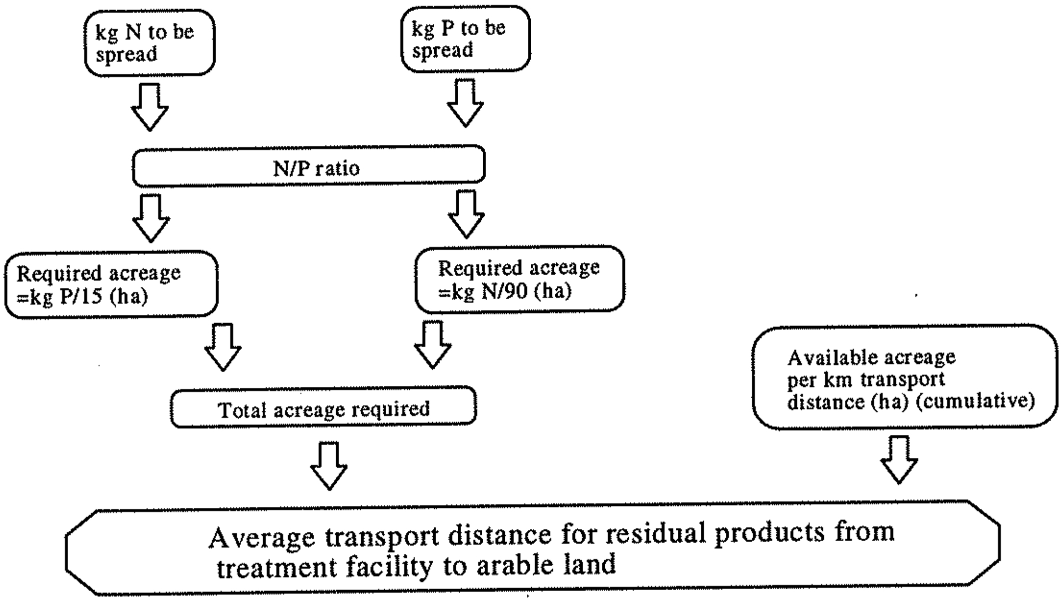

Figure 6. Structure of the distance calculation sub-model.

Data used in the Uppsala case study

The formula that is used in the Uppsala case study is developed using several assumptions and data on the geography of Uppsala county.

- The amount of total nitrogen is limited to 90 kg/ha & year, which is equivalent to approximately 65 kg of mineral N/ha, which is an amount that, in practice, all crops can utilise in one year.
- The amount of total phosphorus is limited to 15 kg/ha & year, which is the average amount of phosphorus removed from arable land per hectare annually in Sweden. This implies that no accumulation of phosphorus will occur due to waste residual products.
- The part of arable land that are considered available for residual products is assumed to be 20% of the total acreage, this assumption is made since approximately 50% of the farms have livestock and consequently do not need more organic fertilisers. Of the remaining acreage, we have assumed that 60% are unavailable for receiving residual products from the urban society for one reason or another. This leaves 20% of the total acreage.
- The driving distance to the fields is assumed to be twice the distance ”as the crow flies”.

Calculations and background data

First the need of arable land is calculated. This is calculated as follows:

$Ra=(N/DN+P/DP)/AL$

- Ra=Required total acreage (ha)
- N=Amount of N-tot. in rest products with $N/P>ND/PD$ to be spread annually (kg)
- P=Amount of P-tot. in rest products with $N/P< ND/PD$ to be spread annually (kg)
- DN=Maximum dose of N/ha and year (kg/ha & year)
- DP=Maximum dose of P/ha and year (kg/ha & year)
- AL=Part of arable land that are available for spreading: 0.20

Subsequently the average transport distance that corresponds to this acreage is calculated. In order to do this, the data on the amount of arable land that surrounds the area under study is required. In Nilsson & Lindberg (1994) the amount of arable land in the surroundings of Uppsala is investigated (Table 9).

Table 9. Arable land within difference distances away from the city of Uppsala (Nilsson & Lindberg, 1994)

Radius (km from the city of Uppsala)	Arable land within the radius (ha)
10	10 000
20	37 000
30	75 000
40	132 000

These data were fitted to a function of the second degree, the result was:

$Arable\ land=80.6*(radius)^2+3035$, corrected r2-value was 0.9995. (1)

This gives:

$Radius = \sqrt{(ArableLand / 80.6) - 37.65}$ (2)

The average distance from the centre to a point within a circular area is $r / \sqrt{2}$. This is the distance "as the crow flies", but since the roads are not straight, the driving distance to reach a specific field may be considerably longer. Consequently, I have assumed a "winding factor" that is 2, i.e. the driving distance is twice the direct distance. This together with formula (2), gives:

$Dd = \sqrt{((Ra / 80.6) - 37.65) / 2} * WF * PU$ (3)

Dd=Driving distance, (km)

Ra=Required acreage (ha)

WF=Winding factor, This factor turns the straight line distance into actual road distance, the figure used is 2.

PU=Part land used, the proportion of the arable land that is available for spreading of residues. Hitherto it has been assumed to be 20%.

Discussion

Validity

The calculations on required acreage are general. The transport distance model can be considered valid when used in Uppsala or any city with the same proportion of arable land in its surroundings and furthermore with a road network similar to Uppsala. However, it is very easy to change formula (3) to be valid for another region just by inserting the actual function (similar to formula (1) and (2)) for the region, the problem may be to acquire that formula.

Future improvement

The model uses a factor that corrects the "straight line" distance to represent the actual road distance. This factor needs to be more accurate in order to predict the distance in a better way. There are also some assumptions used regarding availability of arable land, which should be substantiated to increase the validity of the model.

A major improvement would be if a GIS (Geographical Information System) software could be incorporated with this sub-model, facilitating instantaneous calculations of available farm land and actual driving distances.

References

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APPENDIX 1. DATA FOR THE COMPOST MODEL

Degradation of organic matter

Degradation of C-chmd, C-chfd, C- Fat and C-Protein

The degradation of the above-mentioned components in a real compost is a very complex process with several inter-dependencies between organic matter, pH value, temperature, moisture content, etc. The end products are mainly CO_2 and humus, but some nitrogen compounds (NH_3 and N_2O) are also of interest. In this model, however, it is assumed that the compost is handled in such a way that the conditions are fair, and as a result, the model uses only static relationships to describe the degradation process.

The conclusion of this reasoning is that degradation of each ingredient can be described by a constant that describes how much of the specific organic matter that is turning into CO_2 and humus, respectively. These constants are presented in table 1.

Table 1. Degradation of organic matter in a "normal compost", calculated from the mentioned references (% of incoming that degrades during the compost process)

Material	Haug (1993)	Svensson (1987)	Biocycle (1991)	Chosen value, % of C that forms CO_2
chsd (lignin)	0	0		30 [a]
chfd (sugar, starch)	70	100		80
chmd(Cellulose)	0-90	100	90	90
Fat	50	71		60
Protein	50	81		65

[a] *According to Haug (1993), Svensson (1987) and Biocycle (1991) lignin is not decomposed at all. However, during the post-composting process, the temperature may be appropriate for some white rot fungi, that decompose lignin in topsoil. This led to the conclusion that lignin is decomposed to some extent during the composting process. I have chosen 30% as the decomposed percentage, this assumption is based on Wessén (1983), who measured degradation of leaves and straw in topsoil.*

Nitrogen mineralisation during the degradation of proteins

When the composting process declines due to decreasing access of carbon, the micro-organisms gradually die off. When this happens, some of the nitrogen in the organisms is mineralised by the microbes that are still alive. If the conditions are ideal, mainly NO_3^- is formed, but in practice some NH_4^+ is always present in a mature compost.

Svensson (1987) states that the percentages are :

- $N\text{-}NO_3^-$: 0.184% of DM mature compost.
- $N\text{-}NH_4^+$: 0.0312% f DM mature compost.
- After 12 months composting the N-content was 1.8% of DM, this leads to:
- $N\text{-}NO_3^-$: 0.184/1.8=10.2% of N found in mature compost is $N\text{-}NO_3^-$
- $N\text{-}NH_4^+$: 0.0312/1.8=1.73% of N found in mature compost is $N\text{-}NH_4^+$.

According to SNV (1992), the percentages of nitrogen in mineralised form are: $NO_3^->500$ mg/kg mature compost, stochiometry gives:

- (14+3*16)*500=113 mg $N\text{-}NO_3^-$/kg mature compost.
- Assuming 50% moisture content makes 0.0226% of DM.
- Assuming 1.8% N-tot gives 1.25% $N\text{-}NO_3^-$ of N-tot in mature compost.
- $NH_4^+<0.05$ mg/kg mature compost. The same assumption on moisture and total N content implies: 0.43% $N\text{-}NH_4^+$ of N-tot in mature compost.

The figures used in the model are:

- $N\text{-}NO_3^-$: 6% of N-tot.
- $N\text{-}NH_4^+$: 1% of N-tot.
- The rest, 93% is found in humus, i.e. organically bound.

Degradation of organic compounds

VOC

SNV (1993) measured the content of VOC before and after composting and found that 1.3% of the input remained in the mature compost. I have assumed that, of the disappeared VOC, 75% has been gasified and the rest, 25%, of the lost VOC is degraded. I have no data to substantiate this assumption.

CHX

Since CHX is volatile, as VOC, I assume the same figures as for VOC. 1.3% remains in compost, of the lost amount 75% is gasified and 25% is degraded.

AOX

I have not found any data on AOX in compost. I assume that AOX is not affected by the process.

PAH

According to SNV (1993), 82% of incoming PAH remains in the mature compost. I assume that the rest is degraded during the process. I have no data to substantiate this assumption.

Phenols

According to SNV (1993), 3.5% remains in the compost. I assume that the rest is degraded during the process. I have no data to substantiate this assumption.

PCB

SNV (1993) states that 70% remains in the compost, while Hovsenius (1979) states 50%. I chose 60%. Of the 40% that disappears, I assume half to be degraded and half to be gasified. I have no data to substantiate this assumption.

Dioxin

I have found no data on dioxins in compost. I assume that dioxins are not affected by the process.

APPENDIX 2. CALCULATIONS OF EMISSIONS FROM THE TRANSPORT BLOCKS

Garbage truck

Collecting route

Table 1. Emissions from "collecting route", assuming 0.4 kg diesel per km and 43.1 MJ per kg diesel (Grägg, 1992)

	VOC	CO	NO_X [a]	Particles	CO_2
g/km (Grägg, 1992)	0.74	3.06	15.35	0.41	1278
g/kg fuel	1.85	7.65	38.38	1.025	3021.4
g/MJ used fuel	0.043	0.177	0.89	0.024	74.1
Effect of the filter (Grägg, 1990)	-20%	-16%	+6%	-60%	±0
Final emission, g/MJ used fuel	0.034	0.149	0.944	0.0095	74.1

[a] According to Egebäck & Grägg (1988), NO counts for 90% of NO_X and NO_2 for 10%, this leads to an average N-content in NO_X of 45%.

Table 2. Emissions of sulphate, nitrate and PAH on the particles

	Sulphate	Nitrate	PAH (28)
Emissions (Grägg, 1992)	1.30 (mg/km)	1.97 (mg/km)	75.2 (µg/km)
Recalculated as mg/MJ or µg/MJ	0.075	0.11	4.36
After 60% reduction (Grägg, 1990)	0.03	0.044	1.74

A to B transport

Table 3. Emissions from "A to B transport" (Grägg, 1992)

	VOC	CO	NO_X [a]	Particles	CO_2
g/kWh on driving wheel (Grägg, 1992)	0.33	0.74	8.61	0.20	720
37% efficiency gives; g/kWh in used fuel	0.12	0.27	3.19	0.074	266.4
Effect of the filter (Grägg, 1990)	-20%	-16%	+6%	-60%	±0
Emission, g/kWh used fuel	0.098	0.23	3.38	0.03	266.4
Final emission, g/MJ used fuel	0.027	0.064	0.94	$8.2*10^{-3}$	74

[a] According to Egebäck & Grägg (1988), NO accounts for 90% of NO_X and NO_2 for 10%, this leads to an average N-content in NO_X of 45%.

The particle emissions in this transport mode are 90% of the emissions during the collecting route, I assume that the composition of the particles is the same.

Table 4. Particle-bound emissions from A to B transport with garbage truck

Sulphate, mg/MJ used fuel	Nitrate, mg/MJ used fuel	PAH (28) µg/MJ used fuel
0.026	0.040	1.5

Ordinary truck and Truck and trailer

Table 5. Emissions from "A to B transport" (Egebäck & Hedbom, 1991), (Grägg, 1992)

	VOC (Egebäck & Hedbom, 1991)	CO (Egebäck & Hedbom, 1991)	NO_X[a] (Egebäck & Hedbom, 1991)	Particles (Grägg, 1992)	CO_2 (Grägg, 1992)
g/kWh on driving wheel (Grägg, 1992)	0.63	2.80	11.39	0.22 g/km	720
37% efficiency gives; g/kWh in used fuel.	0.233	1.036	4.21		266.4
Final emission, g/MJ used fuel	0.065	0.29	1.17	0.013 [a]	74

[a] According to Egebäck & Grägg (1988), NO accounts for 90% of NO_X and NO_2 for 10%, this leads to an average N-content in NO_X of 45%.

Calculated using data on fuel consumption from Grägg (1992). Assuming that the compositions of these particles are the same as for garbage truck, we get Table 6.

Table 6. Particle-bound emissions from A to B transport with ordinary truck and truck and trailer

Sulphate, mg/MJ used fuel	Nitrate, mg/MJ used fuel	PAH (28) µg/MJ used fuel
0.041	0.060	2.5

APPENDIX 3. RESULTS FROM SIMULATIONS WITH THE COMPOST MODEL

Table 1. Simulation result for composting of household waste (kg)

Substance	Feedstock		Compost		Gaseous emissions
C-tot	350.0E+3		102.8E+3		247.2E+3
C-chsd	23.4E+3		98.5E+3		0
C-chfd	78.2E+3		0		0
C-fat	108.9E+3		0		0
C-protein	53.2E+3		0		0
BOD	0		0		0
VS	645.1E+3		160.0E+3		0
DM	806.4E+3		326.1E+3		0
CO2-f	0		0		0
CO2-b	0		0		906.3E+3
CH4	0		0		3.2E+3
VOC	1.8		23.1E-3		1.3
CHX	8.1E-3		104.8E-6		6.0E-3
AOX	0		0		0
PAH	403.2E-3		330.6E-3		0
CO	0		0		0
Phenols	22.2		776.2E-3		0
PCB	35.1E-3		21.0E-3		7.0E-3
Dioxins	72.6E-9		72.6E-9		0
O-tot	231.4E+3		50.1E+3		0
H-tot	46.8E+3		7.1E+3		0
H2O	1.5E+6		326.1E+3		0
N-tot	16.1E+3		11.0E+3		5.1E+3
N-NH3/NH4$^+$	0		109.9		4.8E+3
N-NO$_x$	0		0		0
N-NO3$^-$	0		659.4		0
N-N2O	0		0		96.1
S-tot	1.9E+3		1.9E+3		0
S-SO$_x$	0		0		0
P	3.1E+3		3.1E+3		0
Cl	3.1E+3		3.1E+3		0
K	7.5E+3		7.5E+3		0
Ca	22.6E+3		22.6E+3		0
Pb	8.1		8.1		0
Cd	241.9E-3		241.9E-3		0
Hg	80.6E-3		80.6E-3		0
Cu	16.1		16.1		0
Cr	4.0		4.0		0
Ni	2.42		2.42		0
Zn	1.05E+02		1.05E+02		0
C-chmd	86.3E+3		4.3E+3		0
Particles	0		0		0
COD	0		0		0

Table 2. Simulation result for composting of park waste (kg)

Substance	**Feedstock**		**Compost**		**Gaseous emissions**
C-tot	527.8E+3		160.4E+3		367.4E+3
C-chsd	164.2E+3		145.2E+3		0
C-chfd	39.9E+3		0		0
C-fat	0		0		0
C-protein	20.5E+3		0		0
BOD	0		0		0
VS	1.0E+6		254.7E+3		0
DM	1.1E+6		348.6E+3		0
CO2-f	0		0		0
CO2-b	0		0		1.3E+6
CH4	0		0		4.7E+3
VOC	0		0		0
CHX	0		0		0
AOX	0		0		0
PAH	0		0		0
CO	0		0		0
Phenols	0		0		0
PCB	0		0		0
Dioxins	0		0		0
O-tot	444.6E+3		83.1E+3		0
H-tot	45.6E+3		11.2E+3		0
H2O	760.0E+3		348.6E+3		0
N-tot	8.0E+3		8.0E+3		0
N-NH3/NH4^{+}	0		79.8		0
N-NO$_{x}$	0		0		0
N-NO3^{-}	0		478.8		0
N-N2O	0		0		0
S-tot	570		570		0
S-SO$_{x}$	0		0		0
P	1.1E+3		1.1E+3		0
Cl	5.7E+3		5.7E+3		0
K	5.7E+3		5.7E+3		0
Ca	11.4E+3		11.4E+3		0
Pb	14.5		14.5		0
Cd	182.4E-3		182.4E-3		0
Hg	45.6E-3		45.6E-3		0
Cu	18.2		18.2		0
Cr	11.5		11.5		0
Ni	6.16		6.16		0
Zn	7.67E+01		7.67E+01		0
C-chmd	303.2E+3		15.2E+3		0
Particles	0		0		0
COD	0		0		0