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A new model has been developed for evaluating the overall resource consumption and environmental impacts of municipal solid waste management systems by the use of life cycle assessment. The model is named EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) and is able to compare different waste management strategies, waste treatment methods and waste process technologies. The potential environmental impacts can be traced back to the most important processes and waste fractions that contribute to the relevant impacts. A model like EASEWASTE can be used by waste planners to optimize current waste management systems with respect to environmental achievements and by authorities to set guidelines and regulations and to evaluate different strategies for handling of waste. The waste hierarchy has for decades been governing waste management but the ranking of handling approaches may not always be the most environmentally friendly. The EASEWASTE model can identify the most environmentally sustainable solution, which may differ among waste materials and regions and can add valuable information about environmental achievements from each process in a solid waste management system.

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Introduction

In recent years life-cycle-assessment (LCA) has frequently been used to evaluate the environmental issues associated with solid waste management (e.g. Hunt 1995, Björklund *et al.* 2000, Finnveden. *et al.* 2000, Grant *et al.* 2003). The main advantage of using LCA on solid waste management systems is that the approach in a systematic way covers all impacts associated with the waste management, including all processes in the solid waste system as well as upstream and downstream of the waste management system. This provides the capability of evaluating different waste technologies with different patterns of energy consumption or production and different levels of material recovery. For example, landfilling with gas extraction could be more environmentally sound than incineration with no energy recovery. On the other hand if the incinerator recovers energy with high efficiency and the energy produced replaces, for example, coal-based energy production, incineration may be environmentally superior to landfilling. Using LCA on solid waste systems and technologies may hence provide a more detailed and complete assessment of the environmental aspects than, for example, suggested by the waste hierarchy that has ruled waste management during the last couple of decades. The waste hierarchy (Council of European Communities 1991) defines that waste should be minimized or prevented prior to recovery of energy in waste prior to landfilling. The huge amounts of data necessary to complete a full LCA may seem prohibitive but is necessary to ensure reliable results. Moreover, increased use of LCA actually means more data readily available for new cases to be investigated.

Several models for environmental assessment of treatment and disposal of municipal solid waste have been presented in the last decade. The IWM-model (White *et al.* 1995, McDougall *et al.* 2001) applies life-cycle thinking on handling of municipal solid waste and includes first a spreadsheet and later a more advanced model for calculating life cycle inventories. The model is very user friendly and easy to learn but is not in all respects flexible. The ORWARE model originally focused on organic waste from households and industries but has continuously been expanded to include other waste material fractions. The ORWARE model uses a combination of life cycle assessment and substance flow analysis (SFA) and translates and aggregates the results into environmental impacts such as global warming, acidification, nutrient enrichment and photochemical ozone formation (Dalemo *et al.* 1997). This model is very flexible but also difficult to use unless the user has significant experience with the files available in the ORWARE package. The US EPA together with the Research Triangle Institute and North Carolina State University developed a life cycle inventory (LCI) model which calculates emissions, energy offset and costs and has the option of optimizing the system with respect to one criterion (Harrison *et al.* 2001, Solano *et al.* 2002). The Wisard model developed by the Ecobilan (now Price Waterhouse Coopers) performs a full LCA of a waste system. The model handles up to 41 material fractions and many waste treatment methods and technologies that can all be modified by the user. The model has been criticized for not being transparent, not clearly defining system boundaries and providing results that cannot be easily interpreted (Environment Agency 2000).

The existing models have slightly different purposes and they perform life cycle impact assessment on different levels. They also differ in their flexibility to modify input and output from waste treatment methods. The aim behind the model presented in this paper was to meet the need for a user-friendly, well-documented and flexible model, which is able to compare different waste management strategies, waste treatment technologies and simultaneously identify the waste substances or technologies which are the sources of the most important potential environmental problems of the system. In addition, the goal was to include life cycle impact assessment methods that are generally accepted and include new developments in impact categories and impact assessment data where needed.

Another method of evaluating products or systems is by using cost–benefit analysis which increasingly has been used to find the most optimal strategy for waste treatment in respect to economic and environmental costs and consequences. Cost benefit analysis (CBA) have among others been made on beverage containers, paper and organic waste (Danish EPA 1995, Petersen & Andersen 2002, Vigsø & Andersen 2002, Damgaard & Strandmark 2003). A major similarity of the two tools is the system boundaries of the product or system to be evaluated. One important difference between CBA and a life cycle assessment is that the purpose of a CBA is optimizing the benefits of society through an outweighing of economical and environmental consequences on preference-based assumptions. LCA is a standardized tool, which has the purpose of minimizing potential impact on the environment, human health and on resources. The boundaries are thus more narrowly defined because economics are not included (Hansen & Gilberg 2003). However, CBA's are often used on a national level disregarding environmental impacts occurring abroad and focusing on the costs for import of materials.

Model scope and structure

The EASEWASTE model enables waste managers to make environmental assessments of solid waste management systems and to make comparisons among several waste management strategies and waste treatment technologies for a region with a given population and waste generation. The model is a framework in which users can define all necessary data for waste composition, collection, treatment, recovery and disposal and life cycle inventory data for materials and energy used in the waste management system. The model enables the user to identify the processes in the waste management system that provides the most significant contributions to the overall environmental impacts. The environmental impacts are calculated based on the overall environmental exchanges which comprise resource consumptions and emissions to air, water and soil which in the life cycle impact assessment may contribute to environmental impact potentials. The model can be used either at a regional or national level for the purpose of setting guidelines for solid waste treatment or it can be used on a more local level with the purpose of choosing a more environmentally beneficial strategy or to optimize the current system by identifying and improving one or more of the processes that potentially gives the most important potential impacts. The model framework can include several different technologies within each waste treatment method, and comparisons between waste technologies within the same treatment method are thus easily conducted. The environmental impacts can be assessed by applying different life cycle assessment methods. Included in the current version of the model is the EDIP 1997 method (Wenzel *et al.* 1997), but

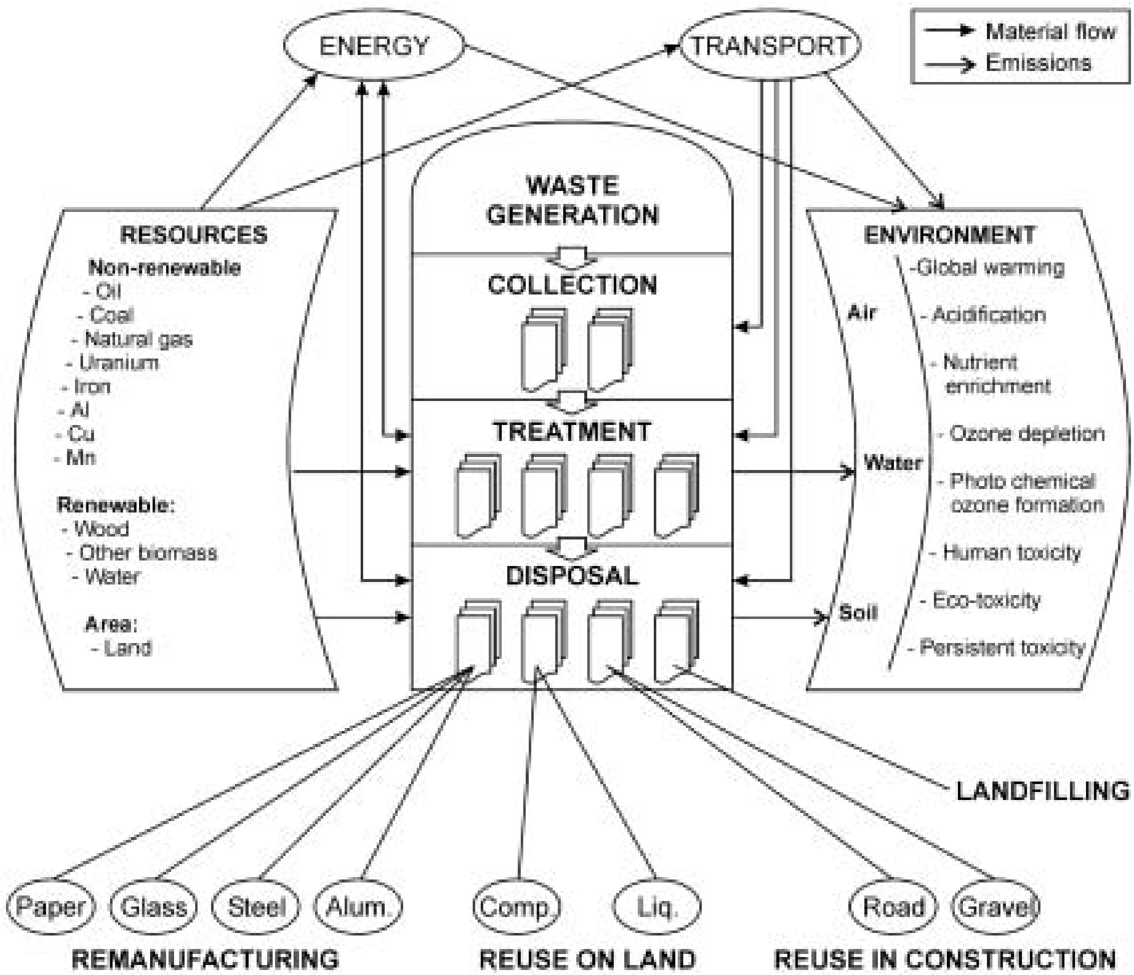

Fig. 1: Conceptual system structure of EASEWASTE.

other methods can be added as they become available and are needed. The EDIP method gives the results in four levels: a life cycle inventory, a characterization of impacts, a normalized impact profile and finally a weighted impact profile (applying political reduction targets). The translation of the environmental exchanges into characterized, normalized or weighted impacts facilitates the comparison of the waste treatment systems' overall environmental performance.

Scope

The scope definition part of the EASEWASTE model is similar to the scope definition of a standardized life cycle assessment, and includes a definition of the functional unit or service provided, an identification of system boundaries and the allocation procedures (ISO 1998). The system boundaries of the model are defined by the waste management system from the point of waste generation and source separation to the point after final disposal of the waste residuals where they become inert, thus not contributing to further environmental impacts as shown in Figure 1. For materials and products used or generated by the waste management system such as fuels, electricity and materials, the system boundaries are consistent with the ISO standards for LCA (ISO 14040 to 14043) in that all environmental exchanges from 'cradle to grave' are included. Figure 2 shows the possible routes in EASEWASTE for treatment, recovery and disposal of municipal solid waste. The processes included are waste collection and transportation, treatment, recovery and disposal, and external energy and materials that are consumed in the system or displaced by recovery of energy and material inside the system. The process datasets for material and energy in the database include life cycle inventories quantifying resource consumptions and emissions to the environment in a life cycle perspective for the process. When a material is recycled or energy is produced they replace external production of similar material or energy, and system expansion of the waste treatment system is used to represent this production in the LCA. Thus, the avoided external productions are included as negative consumptions leading to avoided resource consumptions and avoided emissions. Construction of treatment and disposal facilities and materials used in waste handling can be part of the system if the user defines the material con-

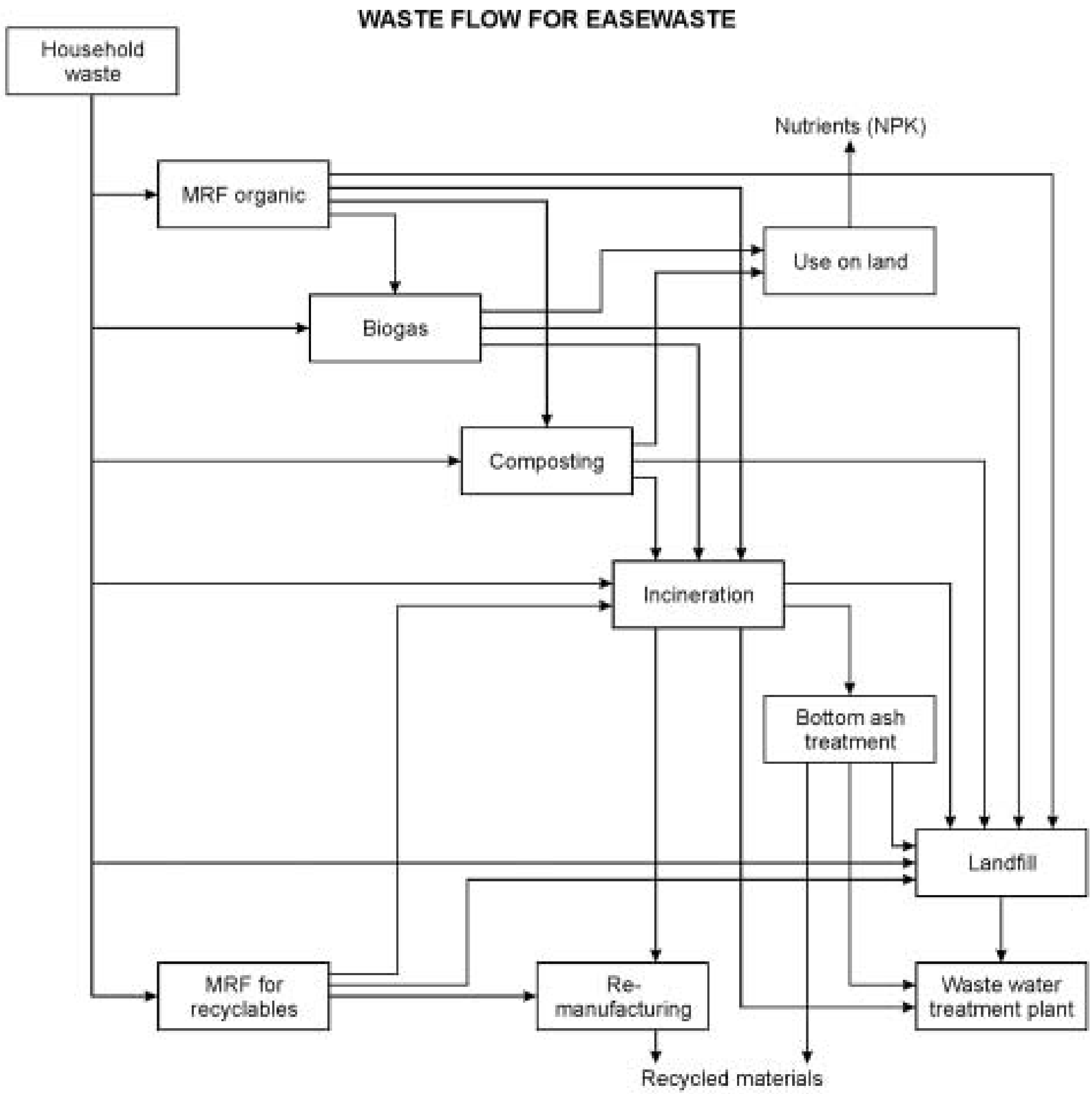

Fig. 2: Possible waste flows in EASEWASTE.

sumptions needed for construction and implements it under the facility. As an example, if it is known how much plastic liner is used for a landfill and what the capacity of the landfill is, the amount of liner used per functional unit can be calculated and included in as consumption under a landfill technology.

The functional unit is a given amount of solid waste generated for an area. The model is able to calculate consumptions of all raw resources as well as all emissions to air, water and soil and generation of solid waste for a solid waste management system.

All substances which are accounted for are defined in a database which can include an unlimited number of substances. Environmental impacts are calculated from the LCI by applying factors which characterize the specific potential impacts for each substance. The environmental impacts which are calculated are also defined by the database, and in principle an unlimited number can be included as defined by the users. The Danish EDIP method (Wenzel *et al.* 1997) is per default part of the model. The default environmental impacts included in the model can be seen in Box 1 and by translating all emissions from one or more scenarios to a set of environmental impacts; assessment and comparison of the scenarios are more easily conducted. Instead of evaluating a result consisting of several hundreds of resource material consumptions and substances emitted to air, water and soil, there is

Box 1: Structure and environmental impacts included in EASEWASTE.

The structure of the life-cycle assessment applied in EASEWASTE.

Goal definition:	Define purpose and target
Scope definition:	What is the functional unit (the service provided by the system)? What are the system boundaries? What are the comparative systems
Scope definition:	What is the functional unit (the service provided by the system)? What are the system boundaries? What are the comparative systems
Inventory:	What are the data requirements? Data collection What is the quality of the data?
Impact assessment:	Which environmental impacts and resource consumptions does the system contribute with? Which contributions are the most significant? Which sources in the system are the most important? Which uncertainties are the most important?

Environmental impacts included in EASEWASTE:
Global warming (CO_2-equivalents)
Acidification (SO_2-equivalents)
Eutrophication (nutrient enrichment, NO_3^--equivalents))
Ozone depletion (CFC11-equivalents)
Photochemical ozone formation (C_2H_4-equivalents)
Ecotoxicity (m^3 soil, water or air)
Human toxicity (m^3 soil, water or air)
Landfilled toxicity (m^3 soil, water or air), see (Hansen 2004) for details
Area use ($m^2 \times$ years)
+ resource consumption of Al, Cu, Fe, coal, oil, natural gas, water, wood, etc.

Levels of result:
Life cycle inventory (g of substances, resources and emissions)
Environmental impacts (g equivalents or m^3 water, soil or air)
Normalized environmental impacts (person equivalents – defined as the impact of one person in a reference year)
Weighted environmental impacts (person equivalents defined as the politically targeted impact of one person in a year)

only a limited number of impacts to evaluate, when the life cycle impact assessment (LCIA) has been calculated. There are no geographical limitations of the model but the user may have to add waste management technologies that are applied in the designated region to obtain results that reflects the actual environmental consequences.

Structure

The EASEWASTE model consists of a set of databases and modules, which together define a scenario of a solid waste system. Modules used in a scenario are taken from the database and copied into the scenario. Thereafter data input can be modified by the user without affecting the database. Figure 3 shows the database and scenario structure that is used. The database also includes all environmental exchanges, both for resource consumptions and for emissions to air, water and soil. For each of the substances emitted to any environmental compartment (air, water and soil) the potential environmental impact factors are defined. The substances are used as environmental exchanges for both waste technologies and for external processes for products and materials that are consumed/produced in the solid waste management system. The database also includes normalization and weighting factors and methods for the life cycle impact assessment (LCIA). The database can be extended continuously by the user with external materials and processes, as well as with waste treatment, recovery and disposal technologies, thereby assuring that the processes needed for a specific assessment can be included. Furthermore, the database with resource material and emission substances that

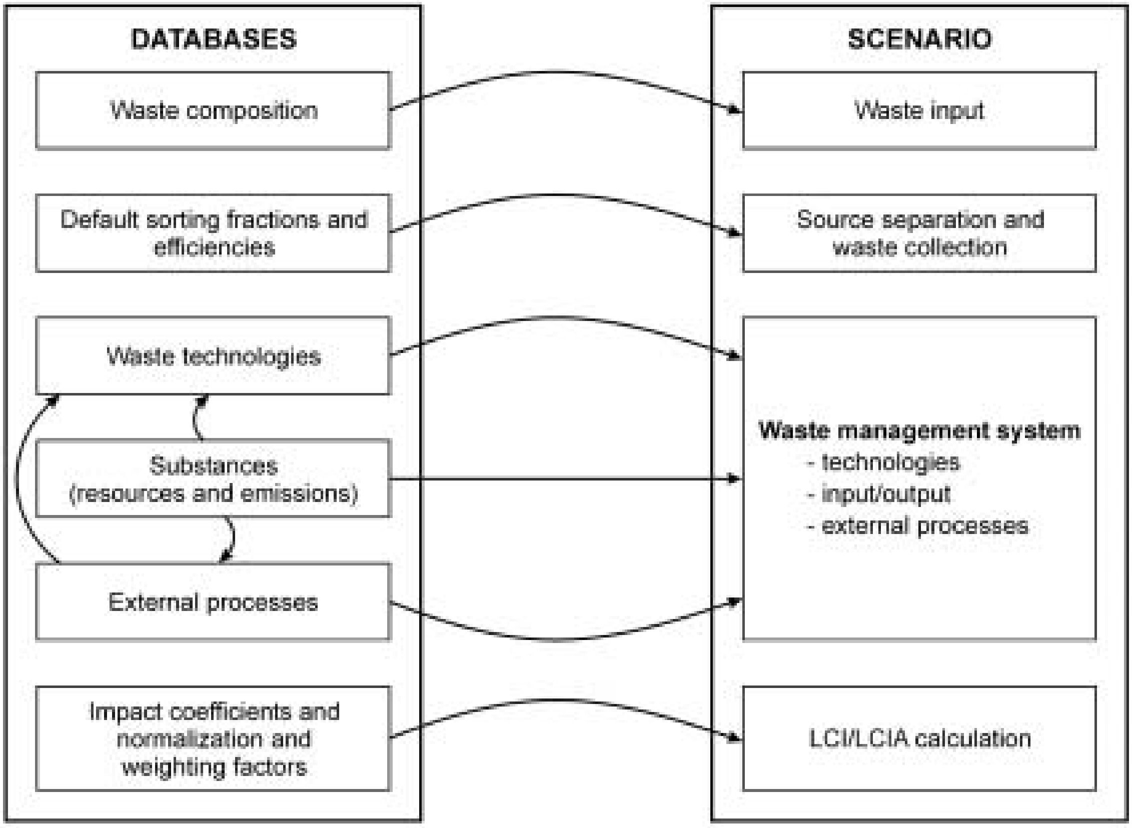

Fig. 3: Database and scenario structure in EASEWASTE.

occur either in an external process or in a waste treatment/disposal technology can be extended by the user.

EASEWASTE is intended to be a comprehensive, flexible and user-friendly model. The modules all have similar designs defining consumptions of materials or energy, and emissions to air, soil and water. The general idea is that the input and output that must be defined by the user, when creating new waste treatment processes, is easily accessible or can be measured at the waste treatment, recovery or disposal facility, and that the equations in the model are generally simple and transparent. Thus, it is possible to model nearly every process by setting the inputs and outputs so these are similar to the actual processes in the waste management system that is being assessed. This should also improve the transparency of the model and the calculations that are done, since all parameters in all modules of EASEWASTE are accessible and can be modified by the user.

Waste management system

The solid waste management system can be defined separately for three different waste generation sources in the area/city that is being assessed in the model. The three waste generation sources are single family housing, multi-family housing, and small commercial business units with waste of a composition similar to household waste. It is important to differentiate between these three waste generation sources whenever differences in waste composition, waste collection, treatment or disposal are significant. Source separation efficiencies for paper and glass and home composting in single family residences are possible explanations and reasons for defining waste management systems separately for the two sources of waste.

For each waste generation source the whole treatment route of collected household waste and residues arising from waste treatment processes is defined. The waste flows which are possible in EASEWASTE can be seen in Figure 2. The modelling of a waste management system in EASEWASTE proceeds through the steps of waste generation, source separation and waste collection, and finally treatment, utilization, recovery and disposal.

Waste generation and composition

The amount of waste generated at each waste generation source is defined by the number of dwellings, number of persons per dwelling and a yearly waste generation per capita; all defined by the user. The composition of the generated waste is defined by 48 material fractions that can be seen in Table 1 and the chemical composition and properties of each material fraction described by the parameters in Table 2. The composition used in a scenario is copied from the default database.

Table 1: Material fractions (48) describing municipal solid waste in EASEWASTE.

No.	Material fraction	No.	Material fraction
1	Vegetable food waste	25	Wood
2	Animal food waste	26	Textiles
3	Newsprints	27	Shoes, leather
4	Magazines	28	Rubber etc.
5	Advertisements	29	Office articles, plastic products
6	Books and phonebooks	30	Cigarette buts
7	Office paper	31	Other combustibles
8	Other clean paper	32	Vacuum cleaner bags
9	Paper and cardboard containers	33	Clear glass
10	Other cardboard	34	Green glass
11	Milk cartons and alike	35	Brown glass
12	Juice cartons with aluminium foil	36	Other glass
13	Other dirty paper	37	Aluminium containers
14	Other dirty cardboard	38	Aluminium trays and foil
15	Kitchen tissues	39	Metal foil (Al)
16	Soft plastic	40	Metal containers (Al)
17	Plastic bottles	41	Other of metal
18	Other hard plastic	42	Soil
19	Non-recyclable plastic	43	Rocks, stones and gravel
20	Yard waste, flowers etc.	44	Ash
21	Animals and excrements	45	Ceramics
22	Napkins and tampons	46	Cat soil
23	Cotton stick etc.	47	Other non-combustibles
24	Other cotton etc.	48	Batteries

Table 2: Chemical composition and properties defining each material fraction in EASEWASTE.

No.	Parameter	No.	Parameter
	Heating value	19	Al
	Methane potential	20	As
		21	Br
1	H_2O	22	Cd
2	TS	23	Cr
3	VS	24	Cu
4	COD	25	Fe
		26	Hg
5	fat	27	Mg
6	protein	28	Mn
7	fibres	29	Mo
		30	Ni
8	C-tot	31	Pb
9	Ca	32	Sb
10	Cl	33	Se
11	F	34	Zn
12	H		
13	K	35	DEHP
14	N	36	NPE
15	Na	37	PAH
16	O	38	PCB
17	P		
18	S		

Waste composition values for fractions and for the chemical properties of each fraction can be modified in the default database or in scenarios without affecting the database.

Source separation and waste collection

Separation of waste at the source is usually applied to achieve clean recyclable or organic waste fractions for subsequent separate treatment. Modelling source separation includes defining types of source separation fractions with corresponding sorting efficiencies, which define the proportion of each material fraction that is led to the sorting fraction. Each sorting fraction is contained in a collection fraction that includes one or more sorting fractions. This allows for a joint collection of separately bagged sorting fractions. For each collection fraction the waste collection system is defined with corresponding fuel consumption for the collection of waste only. Another set of parameters defines the fuel consumption for transportation from the waste collection area to the treatment or disposal facility. From the fuel consumption, the transportation distance is calculated using default fuel efficiencies for the collector trucks, and distances to treatment facilities can thus be a separate parameter to be assessed in the model.

Treatment and disposal

Treatment is defined for each collection fraction by choosing first a treatment method and then a specific waste technology within the chosen treatment method. The treatments are: material recovery facilities (MRF) for organic waste, MRFs for recyclables, remanufacturing of paper, glass, iron etc., anaerobic digestion, composting, use of compost/digested biomass, incineration, bottom ash treatment, use of bottom ash, and landfills for ashes and mixed waste.

Within each treatment or disposal method the database includes a number of waste technologies that can be chosen in a scenario. The waste technology datasets include parameters that define input and output, and default waste technologies that are saved in the database and are then available to be applied in all scenarios. Data in the chosen waste technology is copied from the database to the scenario and can anytime thereafter be changed in the scenario without affecting the default data in the database. Further routing of any residue is defined by transport distances and fuel consumption. Residues from all treatment options have to be routed to subsequent treatment or disposal options until all residues have been routed to final disposal. In this way the waste management systems in EASEWASTE consist of several levels of waste treatment and disposal sub-models each of which is chosen from the database and can be modified by the user.

The model calculates all environmental exchanges from all involved waste technologies including resource consumptions and emissions that occur inside as well as outside the waste management system for products used in treatment and disposal options.

Material recovery facilities

MRFs provide mechanical treatments of the collected waste which often result in several separate waste streams as output. The outputs can be routed to remanufacturing, biological treatment or incineration. In EASEWASTE the MRF modules consist of matrices of transfer coefficients that for each material fraction define the proportion that is routed to the specific output stream. The database in the EASEWASTE model includes MRFs for organic waste, paper and cardboard, glass, plastics and mixed waste, and each of these has different subsequent treatment options. The transfer coefficients and the different output streams enable the user to define different qualities of the waste material and to route the waste outputs from the MRF to different treatments or remanufacturing technologies. Any material or energy consumption can be defined per tonne of treated waste input.

Anaerobic digestion

The anaerobic digestion module in the EASEWASTE model describes the input and output of a system consisting of digestion of organic household waste and combustion of produced biogas. The biogas production is related to the content of volatile solids in each material fraction and to the specific methane potential for each of the 48 material fractions. Since the retention time in the digester is limited, a factor describing the attainment of the potential must be determined by the user for each material fraction. The produced methane may be used for generation of district heating and/or electricity. Energy efficiencies are defined as percentages of the energy content of the gas. The substituted type of energy is chosen by the user from the database for external processes, and avoided emissions from external energy production are subtracted from the emissions occurring at the biogas plant. Air emissions from combustion of the produced biogas are estimated on the basis of the energy content in the biogas. The residue arising from anaerobic digestion, namely the degasified biomass, can be routed to use on arable land as a substitute for mineral fertilizer.

Composting

A pre-treatment or sorting of organic waste prior to composting may be performed in MRF organic. The degradation of the volatile solids in each waste fraction undergoing composting is defined and determines the amount of volatile solids in the outgoing composted waste. The ash content in the waste remains constant throughout the composting process. The outputs from the process are the composted waste and up to three residual fractions from post-treatment or sorting. The user defines the distribution of ingoing dry matter for each waste fraction between the four output fractions. The water content of the composted waste is user defined, since the water content can be controlled during the composting process. This is the water content for all organic material in all four output streams. Only waste fractions which are not able to absorb/desorb water (plastic, glass and metal) will maintain their original dry matter content. The composted waste may be applied to agricultural soil, incinerated or landfilled. The residual fractions can thus be routed to incineration, recycling or landfilling depending on their material composition and quality.

Quantification of air emissions from the composting process are based on the composition of the ingoing waste and the degradation ratio. The nitrogen emissions to air are quantified by the Kirchmann formula (empirical) based on the overall C/N ratio in the waste (Kirchmann 1985). The nitrogen-containing air emissions consist of ammonia, nitrous oxide and nitrogen gas. The emissions of methane and volatile organic compounds are defined as a default percentage of the carbon dioxide released from the composting process. The air emissions can be reduced by gas cleaning, where a reduction percentage is defined by the user for each emission gas.

Use of compost and biomass on arable land

Organic waste treated by composting or anaerobic digestion can be utilized for fertilization or soil improvement in agriculture. The soil application of treated organic waste may substitute commercial fertilizers. The substituted type of commercial fertilizers (nitrogen, phosphorus and potassium respectively) is chosen from the database for external processes, and the model subtracts the avoided emissions and energy consumption from the other emissions of the module.

The majority of environmental impacts from soil application of treated organic waste are also caused by the use of commercial fertilizer. Therefore, to quantify the net impacts from soil application of treated organic waste, comparison to a reference situation is necessary. Simulation of reference scenarios with application of commercial fertilizers and examples of application of treated organic waste substituting a part of the commercial fertilizers are performed by models specifically developed for simulation of soil processes. These simulations enable determination of net emission coefficients for different emissions. Emissions to air (ammonia, nitrous oxide and retained carbon dioxide), surface water (nitrate and phosphorus), groundwater (nitrate and phosphorus) and soil (heavy metals and persistent organic compounds) are quantified, based on the composition of the treated organic waste and the emission coefficients. Improvements in the soil quality as a consequence of the application of treated organic waste are not included in the module, since it has not been possible to quantify this. The use on land module is described in detail by Hansen *et al.* (2004).

Incineration

Waste incineration has the capability of producing district heating and/or electricity and at the same time minimizing waste mass and volume. Apart from these outputs, the incineration module in EASEWASTE has up to six outputs: air emissions, bottom ash, fly ash, sludge, gypsum and waste water. The compositions of each of the six outputs are partly waste related (determined by the composition of the waste) and partly process related (determined by the operation of the process). The waste-specific emissions are calculated with a set of transfer coefficients in a three dimensional matrix $[38 \times 48 \times 6]$ transferring a fraction of each substance in each material fraction of the incoming waste to each of the six outputs. The process-specific emissions are defined separately on the basis of the tonnage combusted at the incineration plant. Additionally, the user can define air emissions on the basis of the total sulphur content in the incoming waste, which typically is relevant for sulphur dioxide (SO_2) and sulphuric acid (H_2S), both of which are waste specific in relation to the total sulphur input (Erichsen & Hauschild 2000). The energy content of the waste is calculated on the basis of the lower heating value of dry matter, the content of total solids and the content of water in each of the 48 material fractions. The energy production is calculated on the basis of the energy content in the waste, combined with user defined energy recovery efficiencies for any relevant type of energy production (district heating and/or electricity).

Produced bottom ash can be routed to bottom ash treatment for later reuse in construction or it can be disposed in a landfill. Fly ash, sludge and gypsum can only be landfilled, and waste water can be treated or discharged to the environment.

Bottom ash treatment and reuse in construction

Bottom ash treatment and reuse in construction consist of two separate sub-modules in EASEWASTE. Bottom ash treatment involves sorting of bottom ash from thermal treatment in order to obtain iron scrap for recovery and screened bottom ash for reuse, in activities such as road construction. The bottom ash treatment module consists of transfer coefficients defining the fraction of each substance to be transferred to up to nine outputs: treated bottom ash, iron small, iron large, copper, aluminium, auxiliary output, air emissions, wastewater and a residue. The model for reuse of screened bottom ash calculates the environmental exchanges connected to distribution and use of bottom ash in construction, subtracting exchanges from any avoided activities. In this case gravel or other raw materials can be substituted, thus extraction and emissions are avoided.

Landfilling

The landfill module in EASEWASTE generates two types of outputs (Figure 4): landfill gas is produced by decomposition of the organic content and landfill leachate is produced by infiltration of water. The gas can either be collected for venting or combustion in an engine or it can migrate up through the top layer of the landfill. The leachate can similarly either be collected and led to surface water or treated at a waste water treatment plant, or the leachate can migrate to the groundwater through the bottom layer of the landfill to the soil and groundwater beneath. All transfer coefficients for landfill gas collection and treatment of landfill gas and leachate are user defined.

Since emissions from a waste landfill are not at a steady level but changing over time, several of the processes are divided into time periods in which parameters for production and handling can be defined. The landfill module operates with four different designated time periods for which user-specified values might vary over time for the following processes and activities.

- Production of landfill gas is defined as a percentage of the total landfill gas potential for each of the four time periods.
- The gas collection system is defined for four periods with collection efficiencies and transfer coefficients for treatment of the collected landfill gas provided for each period.
- Production of leachate is defined as an amount of millimetres per year for four time periods.
- The chemical composition of leachate is defined for four time periods.

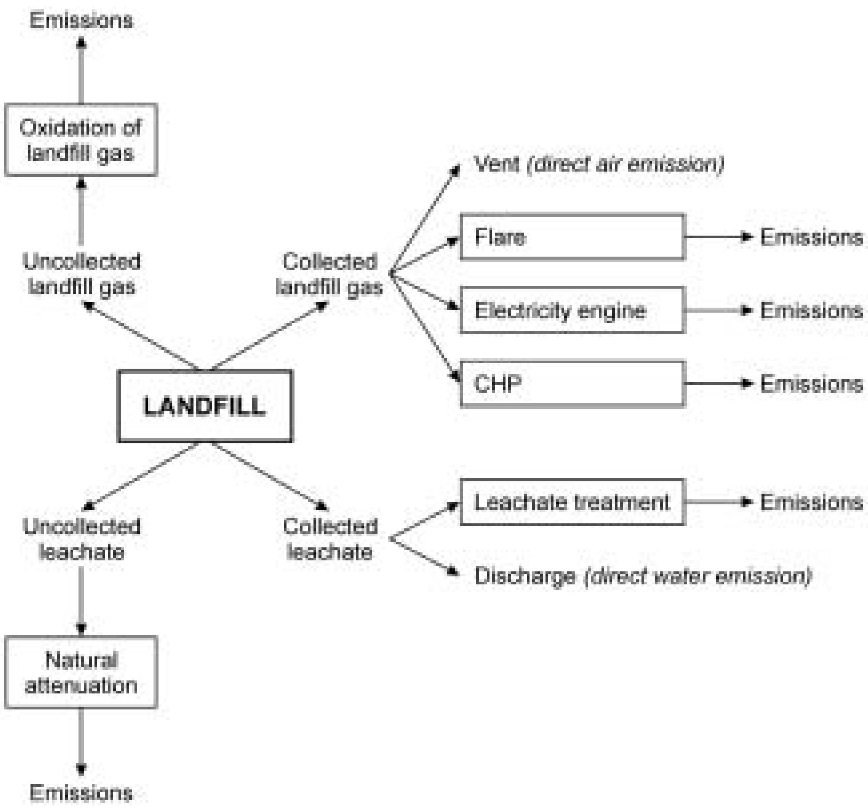

Fig. 4: Landfill gas and leachate options in landfilling module.

- The leachate collection system is defined for four periods with collection efficiencies and transfer coefficients for treatment of the collected leachate and migration to groundwater provided for each period.

The time periods for each of the different processes are totally independent of each other and can be set to as many years as desired. The processes are divided into four separate time periods in order to define different stages of waste landfilling from waste placement, to closure of landfill, active gas and leachate period and a non-active period with no collection of gas or leachate. The overall time frame is equal to the sum of years for each time period and the total time frame can be different for landfill gas and leachate.

The composition of landfill gas is assumed to be steady for each designated period. The amount of potential landfill gas is calculated on the basis of the quantity of organic matter and the methane potential for each material fraction that enters the landfill and with a user-specified concentration of methane in the landfill gas. The landfill module in EASEWASTE currently has four treatment options for the collected gas: vent, combined heat and power engine, electricity producing engine and a flare. Each of these has different energy efficiencies and process-specific emissions. The routing of the gas is defined by a set of allocation parameters for each time period of gas collection.

Leachate is generated over the whole period of the landfill time frame but often with varying amounts due to the different stages in the landfill and due to changes in the top cover and its performance. The leachate generation is defined by the yearly infiltration measured in mm year^{-1} for each of the four time periods. The generated leachate can, like the gas, be collected and treated, or the leachate will migrate through the bottom of the landfill and eventually reach groundwater. The leachate from the landfill has three alternative routings: (1) it may be uncollected and emitted to groundwater with possible natural attenuation of some components, (2) the leachate may be collected, but emitted in untreated form to surface water, or (3) the leachate may be collected and treated at an onsite water treatment plant. The composition of the leachate is defined by the user for all four time periods. Separate definitions for each time period are required because of changes in concentrations especially of salts and biological and chemical oxygen demand (BOD and COD). Furthermore, natural attenuation degradation factors and removal efficiencies for the onsite waste water treatment plant can be defined. For further details on the landfilling module in EASEWASTE see (Kirkeby *et al.* 2004).

Remanufacturing

The remanufacturing module of EASEWASTE has the purpose of comparing the environmental impacts of manufacturing materials from recycled waste material (remanufacturing) and manufacturing materials from virgin resources. The module has the same structure for all recyclable waste materials and calculates the amount of remanufactured material from the waste input, taking into consideration any material loss that may take place during the remanufacturing. The remanufacturing module includes all secondary waste streams and is hence terminal (see Figure 2). Finally, a virgin product or material similar to the remanufactured material can be assumed to be substituted, and the amount of virgin material which is replaced depends on the quality of the recycled material and on the preferences of users of the material. The substitution ratio is defined by the model user (0% ≤ substitution ratio ≤ 100%), and environmental exchanges for the virgin process is assumed to be avoided and will be subtracted from the environmental exchanges for the remanufacturing processes.

Model use and applications

In the following, results from a scenario are described with the aim of illustrating the type of outputs obtained from using the model. Results from the first level are the life cycle inventory which shows all resource consumption and emissions occurring from each process in the waste management system. The next level is the impact characterization which translates and aggregates the values in the LCI into environmental impacts and resource consumption scores. The environmental impact scores are given in a unit corresponding to the impact type, for example, CO_2-equivalents for global warming potential. Toxicity impacts are expressed as the volume of the receiving compartment which may be polluted by the emissions up to a no effect concentration. The third and fourth levels are normalization and weighting. Normalization makes the impacts comparable by relating them to a common reference: the impact of an average person in a year. This is achieved by dividing the impact characterization for each impact potential with the yearly contribution from an average person of the designated impact potential. Normalized results do not show the potential problems or but they show the amplitude of each impact potential compared to the impact potential from an average person in a year. Weighting of the normalized results has the purpose of expressing the relative importance of each impact category in weighting factors, which are typically both politically and scientifically based.

The scenario, for which results are shown, is a waste management system handling approximately 150 000 tonnes of municipal solid waste with four source separation fractions: Organic waste for anaerobic digestion, paper for remanufacturing, glass for remanufacturing and a residual fraction that is directed to incineration with heat and electricity recovery.

Table 3: Scenario example: mass flows and treatment methods.

Treatment and disposal method	Input	Unit
MRF organic	34092	tonne
Anaerobic digestion	23262	tonne
Waste incineration	83511	tonne
Use on land	20210	tonne
Bottom ash treatment	16837	tonne
Reuse in construction	12261	tonne
Remanufacturing, iron scrap	1633	tonne
Remanufacturing, paper and cardboard	31911	tonne
Remanufacturing, glass	8317	tonne
Landfill	5495	tonne

Both heat and electricity production is assumed to substitute coal-based production because the local combined heat and power plant mainly used coal as energy source. The amounts for each treatment can be seen in Table 3 and Figure 5 shows the normalized potential environmental impacts occurring from the waste management system, illustrating that there is a remarkable avoided emission of global warming gases especially due to energy recovery from incineration. However, incineration also contributes to human toxicity potential via water, and detailed investigations in the LCIA (Table 4) shows that the impact arises predominantly from air emission of mercury present in the combusted waste due to very low cleaning efficiencies for mercury at the incineration plant. The digested biomass from the biogas plant is used on arable land as a substitute for commercial fertilizer, thus avoiding

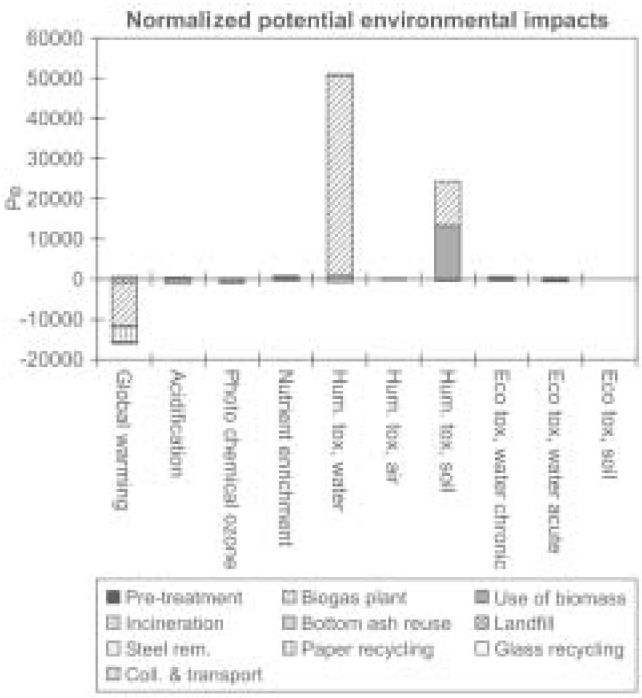

Fig. 5: Normalized environmental impact profile for waste treatment scenario.

Table 4: Selected emissions and their normalized contributions to central environmental impacts.

Emission	Human toxicity potential (water) PE	Human toxicity potentials (soil) PE	Global warming potential PE
As to air	3.3	5900	0
As to water	–0.05	0	0
As to soil	0	12000	0
Carbon dioxide (CO_2)	0	0	–13000
Carbon monoxide (CO)	0	0	–1.1
Cd to air	21	22	0
Cd to water	–4.7	0	0
Cd to soil	0	44	0
Hg to air	49000	4800	0
Hg to water	–310	–30	0
Hg to soil	1100	100	0
Total	50000	23000	–13000

emissions arising from production and use of these. However, human toxicity potential via soil is very significant from use of digested biomass and is caused by the content of arsenic in organic waste. The environmental impact for eco toxicity acute is probably irrelevant, since this is a short-term impact for direct water emissions, which are of less importance in most waste management systems. Figure 6 shows the normalized resource consumption of some selected resources. The figure illustrates that, in particular, the energy resources are being used or saved by the solid waste management system.

Discussion and conclusions

This paper presents a sophisticated and yet user-friendly model for the assessment of resource consumption and potential impacts for waste management systems in a life cycle perspective. The waste input, waste collection method and all treatment and disposal options are made flexible and modifications are easily done by the user, who could be research staff, waste planners or legislative consultants. The model can be used to make comparisons between two or more different waste strategies or it can help to identify the processes or waste sources that contribute strongly to specific environmental problems. The EASEWASTE model takes a very holistic approach to the assessment of the impacts by attempting to cover all relevant resources and environmental impacts. However, the user must keep in mind that the model is a decision-support model and not a model for making decisions. There are other concerns to consider when choosing or optimizing a solid waste management system: economic costs which may be included in the model at a later stage, odour, dust, noise, ethical issues and social willingness towards a waste management system.

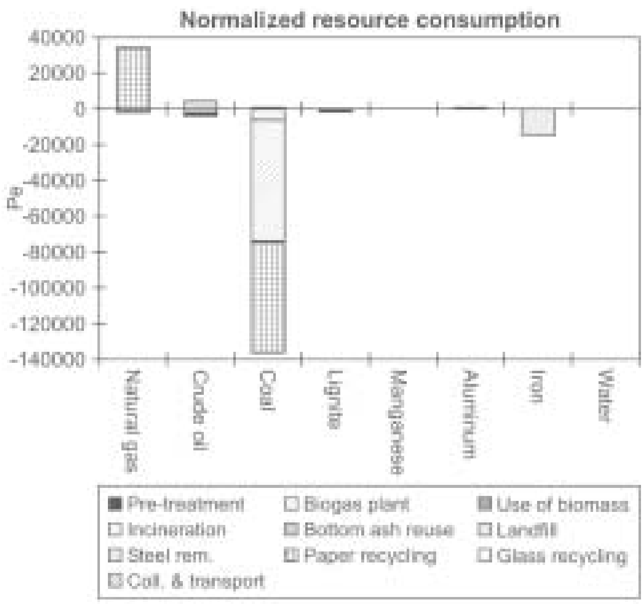

Fig. 6: Normalized resource consumption in example.

Sensitivity and uncertainty analysis should be performed by the user to secure the validity of the assessment – any important factors can easily be identified by varying model input parameters. All important input parameters identified by the sensitivity analysis must be examined to certify that input data are correct. Unfortunately no automatic sensitivity and uncertainty analysis can be made in the existing version of EASEWASTE so this has to be made manually, first by realistic ranging of the most important parameters that influence one or more of the potential environmental impacts.

Even though versatility has been a goal in developing the model, an application can be restricted by the modelling structure and treatment options of the EASEWASTE model. The treatment options can be modified with user-defined emissions to air, water and soil but the number and routing of the produced solid residues are limited by the structure of each module. New complex waste technologies cannot easily be included in the model if they do not fit into the structure of any already created module.

The treatment, recovery and disposal options are chosen to be either process specific or waste specific and this structure cannot be changed by the user. This may limit the use if new knowledge changes the perception and thus makes the choice of the methodology invalid. The waste composition is also restricted to the predefined waste material fractions and their chemical properties. Evaluation of waste with a significant content of a substance not available in the waste composition, such as an organic chemical may thus create errors and misleading recommendations. While the EASEWASTE model can help by evaluating the environmental impacts arising from a solid waste management system, other concerns must also be addressed when choosing treatment and technologies for a solid waste management system. Costs are probably one of the most important factors when choosing a solid waste system but also issues such as odour, hygiene, social acceptability for waste generators, as well as for waste collectors and workers, must also be taken seriously.

The EASEWASTE model can add valuable information about the environmental achievements from each process in a designated waste management system. The model has been used to evaluate two different scenarios for handling of organic household waste in the second largest city of Denmark. The evaluation was supported by an economical evaluation prior to choosing the final system for handling organic household waste. Other municipalities in Denmark have already shown interest in applying the model on their waste system in order to identify areas of potential improvement. A new version of EASEWASTE is currently being developed to include cost and environmental impact as well as a module to conduct sensitivity analysis.

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