LCA Methodology

Waste Treatment in Product Specific Life Cycle Inventories

An Approach of Material-Related Modelling

Part I: Incineration (Int. J. LCA 3 (1) 47-55 (1988))
Part II: Sanitary Landfill

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Abstract

The final disposal of waste in sanitary landfills generates environmental impacts in the form of gaseous emissions and effluents in the seepage water. In product specific Life Cycle Assessments, these environmental impacts resulting from the disposal of the product under study frequently have a strong influence on the overall results. The Sanitary Landfill (SL), like the Municipal Solid Waste Incineration (MSWI), is a complex system with a large variety of different types of waste with varying input composition. A direct determination of the environmental impacts resulting from the landfilling of a single input component, e.g. by measurements, is not possible. The model approach described in this paper shows an operationalized concept for the allocation of the environmental effects caused by the landfill process to special input components. The calculation of the landfill emissions in the model is based on the emission spectrum (landfill gas and seepage water) of an average-sized landfill in Germany and the elementary composition of the single waste fraction under consideration. The resulting reactor landfill module comprises an average split for diffuse and captured landfill emissions, the use of captured landfill gases in a gas engine and a cleaning of captured seepage water in a waste water treatment plant. A short case study demonstrates the calculation of the effects of landfilling of a defined waste fraction (bottle fraction in post-consumer plastic waste).

Keywords: Allocation, landfill; environmental impacts, sanitary landfills; landfill emissions, environmental impact; landfill modelling; MSMI; Municipal Solid Waste Incinerators (MSWI); sanitary landfills (SL); SL; waste management, LCA

Abbreviations:

e_i :	quantity of substance i per Mg waste [g/Mg], i = CO_2, CH_4,...
j :	indicator element, j = C, N, S, Cl, ...
m_j :	mass of indicator element j per Mg waste [g/Mg]
$e_{methane}$:	raw emission of methane per Mg waste [g/Mg]
$m_{c\ (polymer)}$:	non-inert quantity of index element C in the polymer part of the waste
(DW) :	domestic waste
(WF) :	waste fraction

1 General Aspects

Landfills for municipal solid waste are waste treatment plants with a broad input spectrum and a complex emission profile. Microbiological processes and elution with precipitation water cause the biochemical transformation of part of the waste and the escape of the reaction products and other soluble and volatile substances via the leachate and the landfill gas.

The degradation processes in a landfill where degradable organic materials are present, e.g. in a landfill for municipal solid waste, can be described as a sequence of different phases. The initial phase concerns the time period from the opening of the landfill until the biological degradation accelerates. In the second (aerobic) phase, the degradation of easily degradable organic material takes place, leading to carbon dioxide generation. This phase is followed by the acid anaerobic phase resulting in the generation of fatty acids, carbon dioxide and some hydrogen. The solubility of many metals increase during this phase. The fourth phase, or the methane phase, is an anaerobic phase characterized by methane production. In the fifth phase, called the maturation phase, only the more stable components remain and the methane production slows down [25].

As these processes continue for long periods of time (several decades) the potential emissions have to be integrated over a certain time period. The model examined in the following assumes that the processes are terminated after 100 years (surveyable time period) and that an almost inert residue then remains. The end of this time period is assumed to correspond with the end of the methane phase when the methane production decreases. In state-of-the-art landfills, the leachate can be captured and cleaned almost completely by the necessary technical equipment. Only a small part of the landfill gas can be vacuumed off, cleaned and used as an energy carrier.

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Life Cycle Inventory studies usually require the input of resources necessary in waste treatment plants with the emissions released being allocated to certain input fractions. Conventional allocation rules which "distribute" all resources used and emissions released over the individual input fractions, for example according to their mass or volume proportion of the input, are unsatisfactory. This is because the total mass continuity condition applies at best for an allocation of this kind, but the continuity condition is usually not fulfilled for individual components. This leads to results which, for example, allocate heavy metal emissions to inputs which do not contain heavy metals.

The concept described in the following allows an allocation, whereby the only emissions allocated to the input fraction under study are those which can be formed from this input fraction.

2 Model Approach

The model approach is explained by means of an operationalized concept in which the individual steps are described for the derivation of the emission and for the resource allocation to a certain input fraction.

2.1 Emission spectrum of landfill

The emission spectrum of an average-sized landfill for domestic waste (DW) (before the treatment of landfill gas and leachate) is derived from the literature [2-9,11-24] according to quantities:

- landfill gas formation potential [Nm^3 per Mg waste]
- quantity of leachate (= quantity of precipitation) in 100 years [m^3/Mg waste]

and according to composition (individual substances).

The quantities of individual substances released per Mg domestic waste e_i (DW) can be estimated from this. The substances documented are subdivided into two classes:

- substances which are probably brought into the landfill directly as constituents of the waste ("non-formable substances") and
- substances whose biochemical synthesis is considered to be possible or which can be considered as products of decomposition ("formable substances").

2.2 Derivation of indicator elements

Chemical elementary compositions are calculated for the "formable substances". For every substance, a chemical element is determined whose availability limits the formation of this substance (indicator element). The result of this are groups of substances, each of which is assigned to one indicator element. For further calculations, the mass m_j (DW) of each indicator element j emitted per Mg domestic waste (DW) and the corresponding substance quantities $e_{i,j}$ (DW) are relevant. The central hypothesis for further procedure assumes that a mass unit m_j of an indicator element causes a certain emission pattern with the substance quantities $e_{i,j}$.

2.3 Characterization of the waste fraction

For each waste fraction (WF) under study, an estimate is made as to which constituents can be assumed to be permanently inert and which are subject to elution and/or decompose biochemically at landfill ("non-inert")[1]. The quantities (mass) of "non-inert" indicator elements m_j (WF) brought into the landfill via this waste fraction must be determined from this estimate. The "non-inert" parts of the heavy metals (class of "non-formable substances") in the waste fraction are released completely via the leachate.

2.4 Determination of the specific (Raw) Emissions

The emission patterns specific to the indicator elements are transferred to the waste fraction under study by first forming the proportional numbers k_j:

$$k_j = \frac{m_j(WF)}{m_j(DW)}$$

for the indicator elements present in the waste fraction. The specific (raw) emissions are then determined according to type and quantity proportion via the indicator elements present. The absolute quantities can be derived from the following equation

$$e_{i,j}(WF) = e_{i,j}(DW) \cdot k_j \quad [g / Mg].$$

2.5 Reactor landfill model

The raw emissions calculated under section 2.4 (leachate constituents and landfill gas constituents) correspond to the "reactor" module in the "reactor landfill" model (→ *Fig. 1*).

The reactor landfill module represents an average-sized German landfill for domestic waste. The specific landfill gas flow is distributed in a fixed volume ratio among the release flows towards the gas motor (13%), flare (13%) and diffuse emission (74%). This distribution reflects the average conditions in German landfills [16,17,22]. The specific leachate constituents calculated under section 2.4 and their specific masses e_i (WF) in conjunction with the average leachate quan-

[1] Here the "non-formable" substances in the "non-inert proportion" brought into the landfill via the waste fraction under study and released directly again as emissions are also identified according to quantity and type.

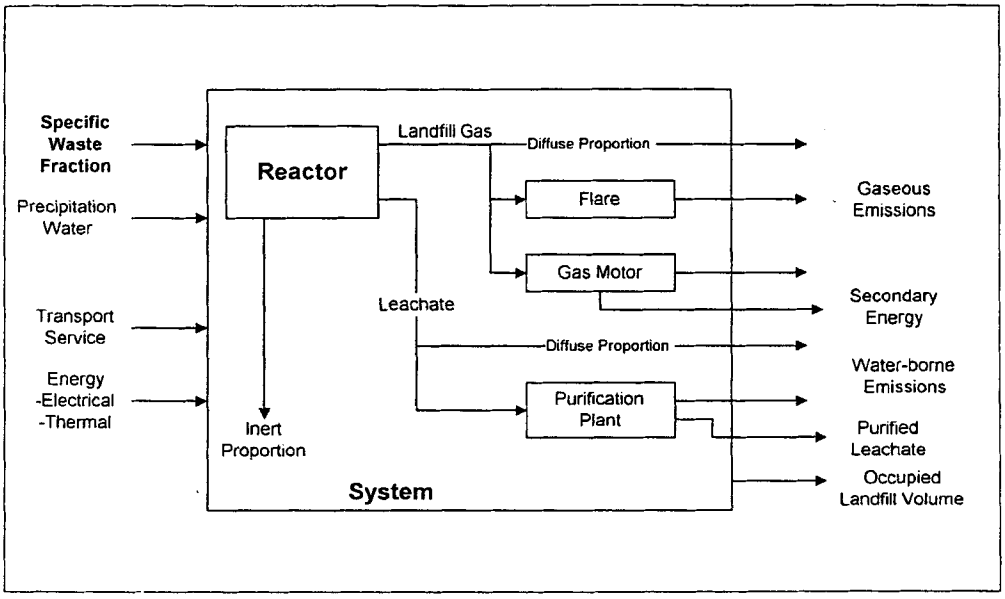

Fig. 1: Life Cycle Inventory Module "Landfill" with Input and Output Flows

tity produce a leachate volume with the corresponding concentrations of contaminations. For the leachate flow, we assume that 90% of the leachate is captured in collecting systems and 10% leaves the landfill as diffuse emissions. The captured leachate flow is sent to an effluent treatment of the type to be found in communal waste water purification plants.

On the basis of a combustion calculation and of emission data [7,9,10,22,24], the reactor landfill model calculates the emissions of flare and gas motor, and the useful energy produced with the gas motor. Emissions from the purification plant and the composition of the purified effluent are also calculated in the reactor landfill model via a submodule "municipal sewage treatment plant". The heavy metals contained in the leachate during the purification are assumed to be bound in the sewage sludge according to their individual retention potential.

3 Submodule – Municipal Sewage-Treatment Plant

The sewage treatment included in the landfill module is calculated from a mix of German municipal plants. Hence, 2% of the population in Germany are connected to plants that use purely mechanical purification, 13.7% to mechanical-biological plants, 38% to plants with additional phosphate disposal and 46.3% to plants with additional nitrogen disposal (according to [28]).

The average efficiency for sewage purification is shown in Table 1.

Sewage constituents for which no purification data can be given are discharged again with the purified sewage.

Phosphate is removed by precipitation with iron III chloride. The resulting iron phosphate remains in the sewage sludge. The chloride is discharged with the water.

The retained heavy metals and some of the AOX are bound in the sewage sludge (→ *Table 2*).

Table 1: Purification efficiency in the municipal sewage-treatment submodule

Parameter	Degree of purification
COD	86.7%
BOD5	94.4%
Ammonium (NH_4^+)	50.1%
Total phosphorus (P)	83.4%
AOX	39.2%

Table 2: Degrees of retention of heavy metals [26] and AOX [27] in sewage sludge

Substance	Degree of retention
Copper	50%
Lead	80%
Cadmium	50%
Mercury	80%
Chromium	60%
Nickel	40%
AOX	40%

All the purification stages yield raw sludge, which is stabilized anaerobically, conditioned with organic polyelectrolytes to make it easier to dewater, and mechanically dewatered.

The reduction in the BOD during sewage treatment yields biological raw sludge which generates digester gas when treated anaerobically. For each 1 kg of BOD in the sewage input to the sewage treatment plant, 0.3 m^3 of digester gas is produced. This is used to generate electricity in a gas motor. The combustion of 1 m^3 of digester gas emits 471 g of CO_2, 0.95 g of SO_2, 0.38 g of NO_x and 0.01 g of dust.

4 Case Study – Input/Output Flows for the Landfilling of 1000 kg of Plastic Waste

(bottle fraction from sorting of post-consumer plastic waste)

The following example should demonstrate how the calculation of the effects of landfilling of a single waste component in a sanitary landfill is put into practice. The special waste component studied in the example is the bottle fraction of the post consumer plastic waste normally collected in Germany by recycling systems.

If it is not recycled, this fraction is potentially landfilled with the composition documented in **Table 3.**

The input and output lists given in **Table 5** can thus be derived from the reactor module described above.

For methane and CO_2 (raw) emissions, modelling is based on the following fixed conditions:

$$\frac{e_{methane}}{m_C} = 0.74 \text{ and } \frac{e_{CO_2}}{m_C} = 1.43$$

For the waste fraction under study, m_c is composed of the carbon proportion of the biogenous contaminations and the carbon compounds which can be eluted from the plastics (additives, monomer residues). The molecular weight of these compounds is in a spectrum which makes biological decomposition appear probable. However, it is not clear whether they are as available as other carbon sources for the complicated anaerobic decomposition to methane. For this reason, a sensitivity analysis with the parameter variation

$$0 \leq \frac{e_{methane}}{m_{c(polymer)}} \leq 0.74$$

and correspondingly

Table 3: Composition of the landfilled bottle fraction; principal components in % weight, heavy metals in [g/Mg] (acc. to [29])

	C	H	N	O	S	Cl	F	heavy metals
total	81.84	13.34	0.1	1.86	0.04	0.73	0.002	317.5 g/Mg
polymer part	81.69	13.32	0.1	1.71	0.04	0.73	0.002	303.6 g/Mg
contaminations	0.15	0.02	0.001	0.15	0.001	0.002	-	13.9 g/Mg

The estimation of the non-inert partition differentiates between the polymer part of the waste fraction and the contaminations. The contaminations are assumed to be totally degradable (100% non-inert). It is assumed that approximately 3% of the hydrocarbon content can be degraded during the considered time period for the polymer part (polyethylene) (FINNVEDEN et al. [25] suggest a degradation value between 1 and 5%). The other indicator elements and heavy metals are assumed to be concentrated in the additives. A partition of 60% of each of them is supposed to be leachable. The resulting non-inert quantities of indicator elements are given in **Table 4.**

Table 4: Non-inert quantities of Indicator Elements in the landfilled bottle fraction (including contaminations) in [g/Mg]

Indicator Elements j	C	S	N	Cl	F
m_i [g/Mg]	26003	224	622	4398	12

$$1.43 \leq \frac{e_{CO_2}}{m_{C(polymer)}} \leq 3.46$$

has to be carried out in LCA-studies and its effects on the result has to be discussed.

The effect of this parameter variation is shown for the plastic waste fraction under study. If no methane generation from the polymer degradation is assumed

$$\left(\frac{e_{methane}}{m_{c(polymer)}} = 0.045\right),$$

the methane emission in the landfill module in **Table 5** will decrease from 14.233 g to a value of 818 g per t of waste and the CO_2 emission will consequently increase from 50974 g to a value of 87836 g. The production of secondary energy via the gas motor will decrease from 10 to 0.6 kWh as a result of the lower methane concentration in the collected landfill gas.

Table 5: Input/Output list for the landfilling of 1 t contaminated Bottle Fraction from post-consumer plastic waste (dry)

INPUT		
Residual waste in the form of bottles (dry)		1000 kg
Transport by dumping vehicles		2.22 km
German grid power		0.79 kWh
Heat from natural gas		2743 kJ
Organic polyelectrolytes (aux. mat.)		2.61 g
Iron (III) chloride (aux. mat.)		0.35 g
Precipitation water		1873912 g
OUTPUT		
Occupied Landfill Volume		2.22 m^3
Waste heat from gas-engine		10.11 kWh
Sewage sludge from leachate purification treated, 60% dry solids		0.89 kg
Purified landfill leachate		1873554 g
Emissions into Atmosphere	indicator element	
Methane (CH_4)	C	14223 g
CO_2	C	50974 g
CO	C	40.84 g
NO_x	N	40.02 g
Hydrogen sulphide (H_2S)	S	94.85 g
NMVOC	C	19.83 g
SO_2	S	63.27 g
Dust		0.42 g
Emissions into Water		
COD	C	282.03 g
BOD5	C	58.04 g
Phosphorus (P)	P	0.01 g
Residual nitrogen	N	83.04 g
Nitrate (NO_3)	N	280.05 g
Sulfate (SO_4)	S	307.79 g
Hydrogen carbonate (HCO_3)	C	1176.49 g
Chloride (Cl-)	Cl	4398.18 g
Fluoride	F	11.92 g
Nitrite (NO_2)	N	0.10 g
Ammonia (NH_4)	N	306.45 g
Copper	Cu	27.78 g
Lead	Pb	3.54 g
Cadmium	Cd	0.49 g
Zinc	Zn	77.28 g
Mercury	Hg	0.03 g
Manganese	Mn	0.28 g
Chromium	Cr	2.85 g
Nickel	Ni	0.90 g
Tin	Sn	0.17 g
Vanadium	V	0.24 g
Arsenic	As	0.04 g
Antimony	Sb	0.86 g

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Book Reviews

The First Guide for LCA in Italian Language

"LCA-Istruzioni per l'uso" (LCA-Operating Manual), the first book on LCA in the Italian language, has been published in February 1998 by Prof. Ing. Vanni BADINO and Dr. Ing. Gian Luca BALDO, respectively a Professor of the Politecnico of Turin and a Researcher of the same University as well as of the Italian Office of Boustead Consulting Ltd.

The book provides a brief history about LCA origin and an introduction to the methodology both for students (it is in fact adopted in three Degree Courses in Engineering at the Politecnico) and for LCA practitioners.

Throughout its ten chapters, the authors show a clear exposition of the three main phases of the methodology (Inventory-Interpretation-Improvement). In particular, the sixth chapter introduces Energy Analysis concepts revealing detailed instructions how to perform energy calculations for the Inventory stage. A short description of energy analysis for LCA is also provided.

Finally, in the last chapter, a case study on LCA of engine blocks is reported in order to clarify how to apply the methodology to a real case.

Reference: Vanni Badino-Gian Luca BALDO, LCA-Istruzioni per l'Uso, Progetto Leonardo, Esculapio Editore (Bologna, Italy), 1998 (168 pages). Lire 22.000.
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Errata

1. *Int. J. LCA Vol. 2, No. 3, pp. 155-162, 1997*
Open-Loop Recycling: Criteria for Allocation Procedures
Tomas Ekvall, Anne-Marie Tillman
p. 159: Equations (16) - (18)
The minus symbols should be plus symbols:
V1+W3, R1+R2, V1+W3

2. *Int. J. LCA Vol. 2, No. 4, pp. 187-194, 1997*
The CML Story:
How Environmental Sciences Entered the Debate on CA
Heinz Gabathuler
p. 193: The footnotes 1-15 do not appear in the running text. We can provide the complete text on request (address: Executive Editor)