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TNO-report

Validation of landfill gas formation models

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Colophon

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Abstract

Models for landfill gas formation were validated and the model parameters were estimated. This was done by a correlation of waste-data and landfill gas formation on nine Dutch landfills, using the mathematical tool SAS. The waste-data (the amounts of waste, waste age and composition) were obtained from the landfill exploitant. Landfill gas formation was calculated from the amounts of landfill gas recovered and the recovery efficiency. The recovery efficiency was estimated from the lay-out of the recovery system, geometry of the landfill, the composition of the top-layer and other site-specific factors.
The majority of observed landfill gas formation could be described with a relative error of less than 30%, using the landfill gas formation models and model parameters as presented in table A1. The description of landfill gas formation improves, going from the zero-order model, to the first-order and the second order model, to the multi-phase model.

Table A1 Landfill gas formation models

– Zero order model	$\alpha_t = \zeta 1.87 \times k_0 A$	$\zeta\, k_0 = 2.4$ kg tonne^{-1} y^{-1}
– First order model	$\alpha_t = \zeta 1,87 A C_0 k_1 \times e^{-k_1 t}$	$\zeta = 0.58$ $k_1 = 0.094$ y^{-1}
– Multi-phase model	$\alpha_t = \zeta \sum_{j=1}^{3} 1.87 A C_{0,i} k_{1,i} \times e^{-k_{1,i} t}$	$\zeta = 0.58$ $k_{1,1} = 0.185$ y^{-1}; $k_{1,2} = 0.100$ y^{-1} $k_{1,3} = 0.003$ y^{-1}
– Second order model	$\alpha_t = \zeta 1.87 A k_2 \left(\frac{C_0}{k_2 C_o t + 1} \right)^2$	$\zeta = 0.64$ $k_2 = 0.0012$ tonne kg^{-1} y^{-1}

In this table α_t is the landfill gas formation in m^3 per year, ζ is the generation factor, k_n are model parameters, A is the amount of waste in place in tonnes; C_0 and $C_{0,i}$ are the amount of organic carbon in the waste and the amount of organic carbon of a specific fraction in kg per tonne, respectively; t is the time in years, elapsed since the depositing of the waste; the factor 1.87 has the dimension m^3 per kg.

The models in table A1 can be used for estimating landfill gas formation in The Netherlands. The results of this estimation should be regarded with some care, since relative errors, larger than the 30% mentioned before remain possible. The applicability of these models in other countries may be limited as a result of differences in waste composition, treatment and regional climate conditions.

Although the multi-phase model describes landfill gas formation best for the nine landfills, this does not mean that in general use of the multi-phase model results in better estimates for landfill gas formation.

Samenvatting

Modellen voor stortgasvorming zijn gevalideerd en de modelparameters zijn vastgesteld. Dit is gebeurd door de afvalgegevens en de stortgasvorming op negen Nederlandse stortplaatsen aan elkaar te correleren. De afvalgegevens zijn opgevraagd bij de stortplaatsexploitanten. De stortgasvorming werd berekend uit de hoeveelheden gewonnen stortgas en het winningsrendement. Dit winningsrendement werd geschat op basis van de lay-out van het winningssysteem, de geometrie van het afvalpakket, de samenstelling van de toplaag en andere stortplaatsspecifieke factoren.
De meeste aldus berekende hoeveelheden gevormd stortgas konden tot op 30% nauwkeurig worden beschreven, gebruik makende van de modellen uit tabel S1. De beschrijving verbetert, gaande van het nulde-orde model naar het eerste- en tweede-orde model, naar het multi-fase model.

Tabel S1 Modellen voor stortgasvorming

– Nulde orde model	$\alpha_t = \zeta 1{,}87 \times k_0 A$	$\zeta\, k_0 = 2{,}4$ kg ton^{-1} j^{-1}
– Eerste orde model	$\alpha_t = \zeta 1{,}87 A C_0 k_1 \times e^{-k_1 t}$	$\zeta = 0{,}58$ $k_1 = 0{,}094$ j^{-1}
– Multi-fase model	$\alpha_t = \zeta \sum_{j=1}^{3} 1{,}87 A C_{0,i} k_{1,i} \times e^{-k_{1,i} t}$	$\zeta = 0{,}58$ $k_{1,1} = 0{,}185$ j^{-1}; $k_{1,2} = 0{,}100$ j^{-1} $k_{1,3} = 0{,}003$ j^{-1}
– Tweede orde model	$\alpha_t = \zeta 1{,}87 A k_2 \left(\frac{C_0}{k_2 C_o t + 1} \right)^2$	$\zeta = 0{,}64$ $k_2 = 0{,}0012$ ton kg^{-1} j^{-1}

In deze tabel is α_t de stortgasvorming in m^3 per jaar, ζ is de vormingsfactor, k_n zijn de modelparameters, A is de hoeveelheid afval in ton; C_0 en $C_{0,i}$ zijn de hoeveelheid organische koolstof in het afval of in een zekere fractie van het afval in kg per ton afval; t is het aantal jaar, verstreken na depositie van het afval; de factor 1.87 heeft de dimensie m^3 per kg.

De modellen uit tabel S1 kunnen worden gebruikt om de stortgasvorming te voorspellen. De resultaten van deze schatting dienen echter met de nodige voorzichtigheid te worden geïnterpreteerd, aangezien in specifieke gevallen de fout veel groter kan zijn, dan de hiervoor gegeven 30%. Alhoewel de stortgasvorming in deze studie het best wordt beschreven met het multi-fase model, wil dit niet zeggen dat voorspellingen met het multi-fase model in de regel nauwkeuriger zijn dan voorspellingen met bijvoorbeeld het eerste-orde model.

Symbols

A	amount of waste in place	tonne
c	constant in reaction equation	-
C_0	original amount of organic carbon in the waste	kg tonne^{-1}
C_t	organic carbon content of the waste at a certain time	kg tonne^{-1}
k_0	model parameter zero-order model	kg tonne^{-1} y^{-1}
k_1	model parameter first-order model	y^{-1}
$k_{1,i}$	model parameter multi-phase model	y^{-1}
k_2	model parameter second-order model	tonne kg^{-1} y^{-1}
n	power in reaction equation	-
n_{lf}	number of landfills	-
Q	a factor, which describes the accuracy of a model	m^3 y^{-1}
t	time elapsed since depositing	y
α_c	calculated landfill gas formation	m^3 y^{-1}
α_o	observed landfill gas formation	m^3 y^{-1}
α_t	landfill gas formation at a certain time	m^3 y^{-1}
ζ	generation factor	-

Table of contents

1 Introduction

Most of the municipal solid waste, produced in The Netherlands, is landfilled. Through anaerobic bacteriological processes the biodegradable organic compounds in the waste are converted into landfill gas. This landfill gas is a mixture of mainly methane and carbon dioxide, but it contains also numerous toxic and odorous components. The mean methane content of Dutch landfill gas is about 57% [Coops et al, **1995**].
Emissions of landfill gas causes several problems, both local as global. Local emissions may cause odour nuisance and vegetation damages; at a global scale methane from landfills contributes significantly to the greenhouse effect. Worldwide estimates of emissions from landfills range from 20 to 70 Tg/yr of a total methane emission of about 515 Tg/yr [IPCC, **1992**]. Dutch methane emissions from landfills are estimated 178-576 ktonnes (Gg) per year of a total of 761-1728 ktonnes [v. Amstel et al., **1993**].
Once solid waste is deposited, the emission problem is in place and the only way left for reducing emissions is landfill gas recovery. If the energy content of the landfill gas can be utilized, landfill gas recovery and utilization proves to be one of the most cost-effective ways of reducing methane emissions [De Jager and Blok, **1993**]. Since utilization of landfill gas replaces use of fossil fuels, landfill gas sometimes even is regarded as a renewable energy source.

In 1993 in The Netherlands about 124 million m^3 of landfill gas was extracted, of which 85 million m^3 is utilized. Methane emission reduction by landfill gas recovery in 1993 was 48 ktonnes, carbon dioxide emission reduction by landfill gas utilization was 80 ktonnes [Adviescentrum Stortgas, **1994**]. Due to efforts of energy companies, waste treaters, NOVEM, and the 'Adviescentrum Stortgas' [the landfill gas advisory centre] the number of landfill gas projects is increasing rapidly. About 30 landfill gas projects will be operational by the end of 1994.

For sizing a landfill gas project, an estimate is made of landfill gas formation and recoverable amounts of landfill gas. For this purpose several models are available, described in literature. For the sizing of landfill gas projects, models are used, containing model parameters obtained from practical experiences. The resulting estimates of formation, however, are quite inaccurate: in general an accuracy of about 50% is assumed. But even this range is insufficient to describe the small amounts of landfill gas that are recovered in some landfill gas projects.

There are several possible reasons for the large ranges in landfill gas formation estimates:
- the estimates of the recovery efficiency are not accurate;
- the amount of waste and waste compositions are not accurately known;
- there is an inherent variation in landfill gas formation, caused by the inhomogenity of the landfill, presence of inhibitors or absence of nutrients and other more or less fortuitous factors;
- the models are inaccurate.

Most likely the truth will contain all aspects: the models used at present could use some improvement, but resulting estimates will remain uncertain due to the first three aspects described above

In this study landfill gas formation models are optimized and validated on the basis of several Dutch landfill gas projects.
The objective of this validation is twofold:
- to obtain a better insight in the predictability of landfill gas formation;
- to define models with best estimates of model-parameters for predicting landfill gas formation.

For this purpose amounts of waste and waste composition were retrieved for nine landfills, along with the amounts of gas recovered and some general information of the recovery system and site management.
From this general information a recovery efficiency was estimated, and the landfill gas formation was calculated.
Subsequently amounts of waste and waste composition were correlated to landfill gas formation, using SAS, software for statistical analysis.

In this report some backgrounds of landfill gas formation are described. Subsequently a short review is given of models for landfill gas formation. The way in which amounts of waste and waste composition is interpreted, recovery efficiencies and landfill gas formation are calculated and in which way both are correlated is described in chapter 4. Results of the calculations for nine Dutch landfills are presented in chapter 5, after which the results are discussed. Finally conclusions are formulated.

2 Landfill gas formation

2.1 Formation

When waste is deposited that contains degradable organic components (DOC), these components are converted into landfill gas throughout the years. This landfill gas has a high energy content, because 55-60 percent of the gas is methane. The transformation of DOC into landfill gas proceeds in three phases:

- in the *hydrolysis phase* the solid organic materials are converted into a mixture of soluble organic compounds,
- these soluble compounds are subsequently converted into a mixture of fatty acids, amino acids, carbohydrates and low-molecular compounds,
- ultimately in the *methanogenic phase* landfill gas is formed from these low-molecular compounds.

Because of the inhomogenity of the waste it can last for years, until in all parts of the waste hydrolysis phase is started. At the same time it is possible, that the waste only one meter away is already converted completely into landfill gas. Most likely hydrolysis is the rate-determining step in the process; once the organic material is hydrolyzed, landfill gas is formed rather quickly.

Landfill gas formation on a single landfill is depicted in figure 2.1. During the exploitation period (about 10 to 20 years) landfill gas formation increases as amounts of waste in place increase. After closure of the landfill gas formation reaches its peak and from then on it gradually decreases.

2.2 Variability of landfill gas formation

There are numerous factors, that influence either the amount of landfill gas ultimately formed, or the speed at which it is formed. An overview of these factors is given in figure 2.2. In general these factors are all connected to:

- waste composition, which determines the amount of degradable organic carbon in the waste, which is the raw material for landfill gas. Besides that waste composition determines numerous other factors, such as the presence of nutrients or inhibitors and the humidity of the waste;
- waste treatment. Mechanical pretreatment, homogenisation, particle size reduction and baling, the extent of compactation, the dumping method, the addition of water has significant effects on landfill gas formation;
- site management. Site geometry, landfill gas recovery, leachate water management, top-liner system;
- local or regional climate conditions: temperature, precipitation.

All these aspects differ significantly from site to site. As a result of this, the amount of landfill gas produced per tonne waste and the speed at which the landfill gas is formed, differ from site to site. As a result of this landfill gas production per tonne of waste becomes less predictable.

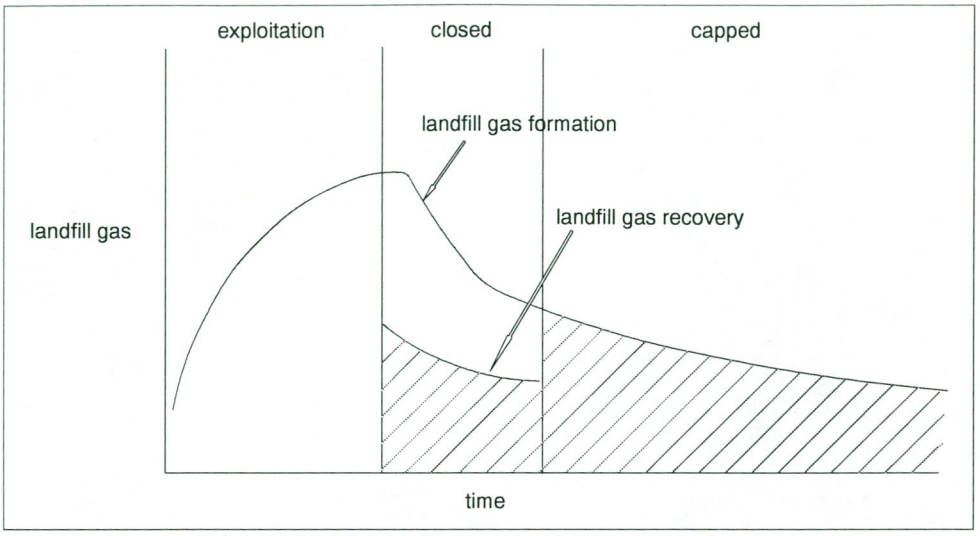

Figure 2.1 Landfill gas formation and recovery on a typical landfill

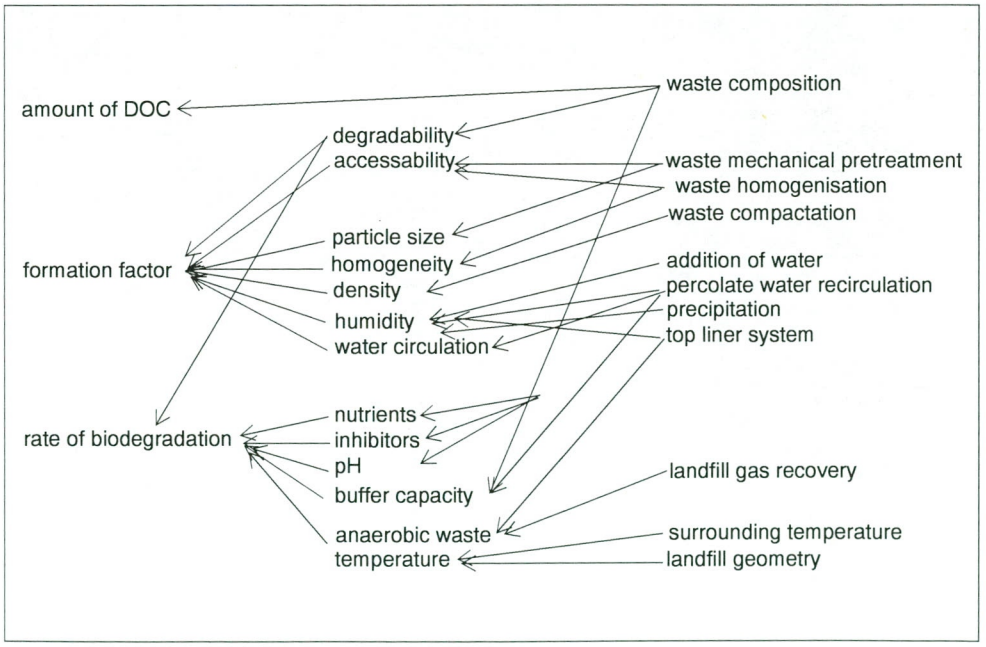

Figure 2.2 Influences on landfill gas formation

3 Modelling landfill gas formation

There are several methods described for modelling landfill gas formation. Extensive overviews are given elsewhere [e.g., Augenstein and Pacey, **1991**; Scheepers and Van Zanten, **1994**], so this chapter will restrict itself to a short overview of models and an indication for their applications. In general, landfill gas formation models are not based on microbiological or biochemical principles, but more on a practical description of formation, as observed in laboratory experiments or in full scale recovery projects.

Landfill gas is formed as a result of the biodegradation of the organic carbon in the waste: per kg of organic carbon that degradates, about 1.87 m^3 of landfill gas is formed. The landfill gas formation on a landfill at some moment in time, α_t, is proportional to the decay of organic material at that time:

$$\alpha_t = -1.87A\frac{dC}{dt} \qquad [3.1]$$

The degradation of organic material can be described as a n^{th} order reaction equation:

$$\frac{dC}{dt} = c \times C^n \qquad [3.2]$$

Assuming that ultimately a certain fraction, ζ (= the generation factor), of the waste is converted in to landfill gas and subsequently solving this differential equation, results in a description of C as a function of C_0 and time, for the different values of the power n. Substitution of these solutions of relation [3.2] in [3.1], results in the formation models as described in table 3.1. The various models are further discussed below.

Table 3.1 Models for landfill gas formation

– Zero order model	$\alpha_t = \zeta 1,87 \times k_0 A$
– First order model	$\alpha_t = \zeta 1,87 A C_0 k_1 \times e^{-k_1 t}$
– Multi-phase model	$\alpha_t = \zeta \sum_{j=1}^{3} 1,87 A C_{0,i} k_{1,i} \times e^{-k_{1,i} t}$
– Second order model	$\alpha_t = \zeta 1,87 A k_2 \left(\frac{C_0}{k_2 C_o t + 1} \right)^2$

– *Zero-order model:*
In a zero order model, landfill gas formation in a certain amount of waste is assumed to be constant in time. So the effect of age is not incorporated. Such a model is applicable for estimating national and global emissions, provided that there are no large changes in waste composition and amounts of waste landfilled. Examples of zero-order approaches are described by Bingemer and Crutzen [**1987**] and US-EPA [**1992**].

– *First-order model:*
The effect of age is accounted for in a first-order degradation model. Landfill gas formation in a certain amount of waste is assumed to decay exponentially in time. This first-order equation is described in numerous cases; e.g. Tabasaran [**1987**]. Verschut et al. [**1991**] correlates measurements on three landfills in terms of a first-order model, the model parameters thus obtained, being the basis of the Dutch estimate of methane emissions in The Netherlands [van Amstel et al., **1993**].
The first order model has been adjusted for several reasons. Ehrig [**1987**] expanded the model with a term expressing the building-up of the methanogenic phase and Hoins [**1986**] introduced a temperature dependency. Hoeks [**1981**] described methanogenesis, assuming several fractions in the waste, all following their own first order degradation. This multi-phase model is so important, that it is described separately below.

– *Multi-phase model*
In the multi-phase model, a number of fractions are distinguished, in which landfill gas formation is described separately. Hoeks [**1981**] distinguished three phases: slow, moderate and fast degradable materials, but other subdivisions are possible, including the introduction of an inert fraction. The multi-phase model has the advantage, that waste composition can be reckoned with, since all types of waste contain typical fractions of slow, moderate and fast degradables. This results in a higher landfill gas production in the first years, and a prolongued formation at the end. In the intermediate years landfill gas formation is less than in the first-order model.

In the sizing of Dutch landfill gas projects, normally this multi-phase model is used. Scheepers and Van Zanten [**1994**] gives a description of this use of the multi-phase model.

— *Second-order model*
In chemistry complex reactions are sometimes described, using a second order reaction equation. An example of this is the catalytic cracking of oil. This process, which consists a large number of reactions, all of a first order but with differing reaction rates, is normally described using second-order kinetics [Weekman and Nace, **1970**]. Since landfill gas formation is also a complex system of different reactions, second-order kinetics might be appropriate. Such a second order model has the same characteristics as a multi-phase model.

4 Method of validation

4.1 General

The essence of the study is the correlation of landfill gas formation to some fundamental waste properties: amounts, age and composition. The way in which these factors are retrieved for the various landfills is described in this chapter, along with the method in which they are correlated. This is done, without going in the details of the nine Dutch landfill gas projects, used in this validation. These results are described in chapter 5.

4.2 Waste amounts, composition and age

Information about amounts of waste deposited throughout the years can be retrieved, through inquiries at the various landfill sites. At some landfills weighbridges are used to measure these amounts, at other sites amounts of waste were estimated from volume of waste deposited. For these years, where information was lacking, amounts of waste were estimated from inter- or extrapolation.

At some landfills, the origin of the waste is also administered, and distinction is made between domestic waste and industrial waste. For sites where this information was lacking it is assumed, that 70% of all waste is domestic waste and 30% is industrial waste.

Amounts of carbon and the degradability of the carbon (slow, medium or fast degradable) is calculated, using the mean composition of landfilled waste, as it has been determined in The Netherlands [Scheepers and Van Zanten, **1994**]. These amounts are given in table 4.1.

Table 4.1 Carbon contents of Dutch municipal waste
*[Scheepers and Van Zanten, **1994**, van Zanten, **1994**, Grontmij, **1994**]*

Fraction	$C_{0,1}$	$C_{0,2}$	$C_{0,3}$	$C_{0,tot}$
Degradability	**Fast**	**Moderate**	**Slow**	
	(in kg tonne^{-1})			
household waste	51	66	19	136
(organic fraction[1])	106			106)
(grey fraction	20	113	33	166)
industrial waste	9	51	51	111
office, shop and services waste	29	92	19	140
sweeping waste	3	93	33	129
demolition waste			11	11
agricultural waste	61	61	13	135
sludge	45	45		90
composting residues	12	63	50	125

1) In The Netherlands organic waste (GFT) is separately collected. The green fraction refers to this separately collected GFT, the grey fraction refers to the rest fraction. In this calculation an efficiency of separate collection of 90% is assumed.

4.3 Landfill gas formation

Landfill gas formation is obtained from amounts of landfill gas recovered and an estimate of the recovery efficiency:

$$\text{formation} = \text{recovery}/\text{recoveryefficiency}$$

A prerequisite for this method of calculating landfill gas formation is, that recovery is optimal. This means that the amount of landfill gas recovered is limited by the amount of landfill gas formed and not limited by other aspects, e.g. the capacity of the blower or the capacity of the utilization.

The amounts recovered were obtained from the landfill sites. The recovery efficiency was estimated using engineers expertise: Grontmij has over a decade of experience in landfill gas recovery design and exploitation at numerous landfill sites in The Netherlands and abroad.
The recovery efficiency of the landfills is estimated from various site-specific parameters, such as the design of the recovery system, the waste body depth, slopes of the side of the landfill, the covering material, the ground level.

Generally, when a landfill is properly designed, vertical wells or a horizontal system are used, the well spacing is less than about 70-100 meters, no clayey top-layer or impermeable top-liner system is applied, the recovery efficiency is about 55%.
In every individual case this efficiency is be adapted, based on the site-specific factors described above.

Some examples:
- the presence of an impermeable top-liner system: recovery efficiency is 60 to 95%, depending on the possibilities for migration landfill gas migration through the soil;
- the presence of a clayey top-layer: recovery efficiency is about 60-75%, depending on the thickness of the layer, the age of the landfill and the possibilities for migration;
- distances between individual wells larger than 100 m: the recovery efficiency is assumed to be 5 to 10% lower;
- steep slopes (> 40°): the recovery efficiency is expected to be about 5 to 10% lower, due to emissions sideways;
- a waste layer, higher than about 20 meters: the recovery efficiency is increases with about 5 to 10% higher;
- a thickness of the waste is smaller than 10 meters: the recovery efficiency decreases with about 5%.

4.4 Correlation of amounts of waste and landfill gas

As described in chapter 3, landfill gas formation can be modelled in various ways. In general, landfill gas formation, α_c, is calculated from waste amount, composition and age, using a model, assuming a formation factor (ζ) and the model parameters (k_1, k_2, etc.). The calculation formation depends on the value of these parameters. So with a fixed set of waste-data, landfill gas formation on a single landfill can be considered as a function of the model parameters.

$$\alpha_c = f(\zeta, k_1, k_2, ...)$$

When for this landfill a gas formation is observed, the difference between the observed and calculated formation is also a function of the model parameters:

$$\alpha_c - \alpha_o = f'(\zeta, k_1, k_2, ...)$$

When sets of waste-data and observed landfill gas formation are available for several landfills, a function Q^2 can be defined, which is the summation of the squares of this difference for all these landfills:

$$Q^2 = \sum_{i=1}^{n/f} (\alpha_c - \alpha_o)^2$$

then Q is also a function of the assumed values of ζ and k_1, k_2, .. :

$$Q = F(\zeta, k_1, k_2, ...)$$

From a mathematical point of view, the function F has its minimum for the value of the formation factor (ζ) and the model parameters (k_1, k_2) that describes the observed landfill gas formations at best. So this function F is a tool which can be used for determining this set of optimum values.

The problem of determining the 'best-fit' model parameters is reduced to a minimization problem, which can be solved numerically.
In this study the minimization is performed using SAS, commercially available software for statistical analysis.

5 Results

5.1 General

In this chapter the results of the study are described. These results are based upon an interpretation of several landfill gas recovery projects in The Netherlands.

For selection of the sites, the two following prerequisites were defined:
- the landfill gas recovery has to be limited by landfill gas formation and not by other factors, e.g. the capacity of the blower;
- the amounts of waste in place have to be known accurately.

Especially the optimum recovery is very important. Many Dutch landfill gas projects proved not to meet this prerequisite, because recovery was sub-optimal. Sub-optimal recovery is e.g., when a landfill produces 10 million m^3 of gas per year and the lay-out of the recovery system makes an efficiency of 50% possible, but recovery is restricted to about 3 million m^3 due to a limited capacity of the blower. In this case the amount of gas recovered and the recovery efficiency do not represent landfill gas formation. An indication for sub-optimal recovery is, that the amounts of gas recovered are close to the maximum capacity of the blower, or that the well pressure is controlled by amounts of gas recovered. In the case of optimum gas recovery the well-pressure is generally controlled by the gas-quality.

Nine landfills in The Netherlands proved to meet both prerequisites. For several landfills, landfill gas formation was estimated for more than one year, so altogether seventeen data-sets were available for the correlation calculations. In the next two sections waste properties and landfill gas recovery and formation are described.
In some landfills, the landfill gas recovery system was expanded throughout the years. These increased landfill gas projects are separately described in the next section, as Bavel1, 2 and 3.

5.2 Amounts of waste in place

Table 5.1 gives an overview of the amounts of waste in place. The amounts and exploitation period in table 5.1 refers to the waste, in which the recovery system is installed. A more detailed description of amounts of waste is given in Appendix 1.

Table 5.1 Characteristics of landfills used in the calculations

Landfill	Exploitation period	Amount of waste (tonnes)
Ambt-Delden	1970-1986	2.317.000
Bavel1	1968-1990	4.936.000
Bavel2	1968-1991	5.460.000
Bavel3	1968-1992	6.000.000
Hardenberg	1974-1988	830.000
Hengelo	1986-1988	846.000
Schijndel	1977-1992	2.258.000
Schinnen	1973-1993	3.145.000
Stainkoel'n	1986-1987	120.000
Vasse	1975-1984	629.000
Veendam1	1976-1992	1.721.000
Veendam2	1976-1993	1.953.000

5.3 Landfill gas formation

Landfill gas formation is calculated from the landfill gas recovery and an estimate of the recovery efficiency:

$$\text{formation} = \text{recovery}/\text{recoveryefficiency}$$

The recovery efficiencies of the landfills are estimated, as described in § 4.3. In estimating the recovery efficiencies the following site-specific factors were regarded:

- the Ambt-Delden landfill is covered with a clay layer, the slopes are not very steep. Recently performed emission measurements proved emissions at Ambt-Delden to be very small [Oonk and Boom, **1995**]. Partially based on these measurements, the recovery efficiency at Ambt-Delden is estimated to be 70%;
- the Bavel landfill site has moderate steep slopes, has a thickness of more than 20 m and is covered with a thick clay layer (beet soil). The recovery efficiency is estimated to be at least about 60%;
- the Hardenberg-Collendoorn site was covered with a bentonite liner in 1992. Since the bentonite is water saturated, landfill gas leakage can be assumed to be very low. This is affirmed by recently performed emission measurements, in which emissions at Hardenberg-Collendoorn were proved to be negligible [Oonk and Boom, **1995**]. Although the top-liner is gas-impermeable, recovery efficiency is not 100%. This is due to the leaking possibilities for gas by migration via the underground. Therefore the recovery efficiency is estimated to be 90%;
- the Hengelo-lob 1 site is a site on a rather small area. The cover material is clay. Landfill gas recovery however, is somewhat hampered by high water-levels in the waste. On top of that, the slopes are steep, so the efficiency is expected to be not very high: it is estimated about 45%;
- in Schijndel part of the surface is covered with clay. When constructing the new compartments, parts of the older waste was covered with a impermeable liner. This means that locally a very high recovery efficiency can be expected. An average recovery efficiency is estimated to be of 75%. This efficiency may be somewhat underestimated, if the permeability of the cover material is lower than expected;

- the Schinnen site consists of a former sand pit without a bottom or slope liner. In 1993 part of the site was covered with a top liner-system of a combination HDPE and bentonite. As a result of this locally the recovery efficiency will be very high. The average efficiency is estimated to be about 65%. The waste, dumped in the years 1991 and 1993, was tipped in a separate compartment with bottom liner, but with limited gas recovery. For this waste a lower efficiency is expected: about 20%;
- in Stainkoel'n a special compartment with an impermeable bottom liner system was built for tipping domestic refuse in the years 1986 and 1987. After this period the compartment was covered with an impermeable top liner. Because the waste is totally wrapped up in impermeable material, the recovery efficiency is expected to be very high: about 95%. This efficiency will be somewhat overrated if the permeability of the liner system is enlarged by leakages;
- in Vasse waste is landfilled in a former sand pit. Years after the landfill was closed, an impermeable top liner was installed and the landfill gas was extracted. Although the emissions through the top cover can be considered negligible, the recovery efficiency is estimated to be only about 60%. A significant amount of methane is expected to migrate sideways. This is possible, because the slope of the pit is not covered with an impermeable liner and because the slopes of the pit is rather steep with a valley in the middle;
- the Veendam site can be divided in two parts: the oldest part is an area with a limited depth. This part was covered with a liner on which new waste was tipped. The recovery efficiency in this older waste is estimated to be 90%. The depth of the upper waste layer is ca 10 m. Since the covering material is not very clayey, the efficiency is limited to about 55%, although this might be higher when the permeability of the top layer is worse than assumed.

An overview of landfill gas formation is given in table 5.2. For older landfill gas projects, landfill gas formation could be estimated for more than one year. In order to avoid, that a few landfills become dominant in the data-set, a maximum was set at four years for a single landfill.

Table 5.2 Landfill gas recovery and formation

Landfill	Year	Recovery ($m^3 y^{-1}$)	Efficiency	Formation ($m^3 y^{-1}$)
Ambt-Delden	1990	6.600.000	70%	9.400.000
	1991	6.300000	70%	9.000.000
	1992	5.200.000	70%	7.420.000
	1993	5.100.000	70%	7.300.000
Bavel1[1)]	1991	10.000.000	60%	16.700.000
Bavel2	1992	12.300.000	60%	20.400.000
Bavel3	1993	16.600.000	60%	27.700.000
	1994	14.900.000	60%	24.800.000
Hardenberg	1993	1.500.000	90%	1.680.000
Hengelo lob 1	1994	2.600.000	45%	5.800.000
Schijndel	1994	16.700.000	75%	22.200.000
Schinnen	1993	13.100.000	65/20%	20. 200.000
Stainkoel'n	1988	2.100.000	95%	2.200.000
	1993	520.000	95%	550.000
Vasse	1992	1.500.000	60%	2.500.000
	1993	1.200.000	60%	2.000.000
Veendam1[1)]	1994	7.000.000	55%	12.700.000
Veendam2	1994	9.600.000	90/55%	17.500.000

1) Bavel1, 2 en 3 and Veendam 1 en 2 refer to various expansions of the recovery systems, as described in § 5.2 of this report.

5.4 Results of the calculations

Landfill gas formation was correlated to amounts of waste and waste composition, as described in section 4.4. The statistical programme SAS had no difficulties, calculating the optimum values of the model parameters in the zero, first and second order model; in case of the multi-phase model, the programme calculated various sets of ζ,$k_{1,1}$, $k_{1,2}$ and $k_{1,3}$, depending on the starting value and often without a physical meaning (e.g., $\zeta = 0.60$, $k_{1,1} = 0.14\ y^{-1}$, $k_{1,2} = 0.06\ y^{-1}$, $k_{1,3} = 0.09\ y^{-1}$; $Q = 0.67$). Most likely whole lines or squares of solutions exist in this multi-phase case. In order to urge the programme to a meaningful solution, the value of ζ was set to 0.58 (as calculated for the first order model), and the value of $k_{1,3}$ was set to 0.030 y^{-1}. SAS calculated subsequently the other two model-parameters, resulting in a satisfactory accuracy.

The results of the calculations are summarized in table 5.3. This table shows the optimum values of the model parameters, as calculated with SAS, along with the values of Q/n_{l_f}. Q is an indicator for the quality of the model, n_{l_f} is the number of data-sets. Minimization of Q was the tool for calculating the optimum set of model parameters (see § 4.4).

Table 5.3 Results of the calculations

Model	Model parameters	Q/n_{lf} (million m^3 yr^{-1})
zero order	ζk_0 = 2.4 kg tonne-1 y^{-1}	2.0
first order	ζ = 0.58	0.71
	k_1 = 0.094 y^{-1}	
multi-phase	ζ = 0.58	0.68
	$k_{1,1}$ = 0.185 y^{-1}	
	$k_{1,2}$ = 0.100 y^{-1}	
	$k_{1,3}$ = 0.030 y^{-1}	
second order	ζ = 0.65	0.72
	k_2 = 0.0012 tonne kg^{-1} y^{-1}	

Table 5.4 Comparison of observed and calculated formation

Landfill	Year	Formation (in million m^3 y^{-1})				
		Observed[1]	Zero order	First order	Multi phase	Second order
Ambt-Delden	1990	9.4	10.3	10.8	9.5	8.6
	1991	9.0	10.3	9.9	8.5	7.6
	1992	7.4	10.3	9.0	7.6	6.8
	1993	7.3	10.3	8.2	6.8	6.1
Bavel1[2]	1991	16.7	21.9	23.1	22.8	22.4
Bavel2	1992	20.4	24.3	25.5	25.4	25.2
Bavel3	1993	27.7	26.7	26.4	23.1	26.6
	1994	24.8	26.7	24.1	26.2	22.3
Hardenberg	1993	1.68	3.7	4.1	3.6	3.1
Hengelo lob 1	1994	5.8	3.8	5.0	4.6	4.2
Schijndel	1994	22.2	10.1	14.4	14.4	13.5
Schinnen	1993	20.2	14.0	17.9	18.7	29.2
Stainkoel'n	1988	2.2	0.5	1.4	1.7	1.9
	1993	0.55	0.5	0.9	0.9	0.8
Vasse	1992	2.5	2.8	2.6	2.1	1.9
	1993	2.0	2.8	2.3	1.9	1.7
Veendam1[2]	1994	12.7	7.7	13.1	11.9	11.6
Veendam2	1994	17.5	8.7	13.6	13.9	13.3

1) The observed formation is derived from the amounts of landfill gas recovered, as described in § 5.3 of this report.

2) Bavel1, 2 and 3 and Veendam1 and 2 refer to various expansions of the recovery systems, as described in § 5.2 of this report.

The calculated landfill gas formation, using these models, are compared with the observed landfill gas formation in table 5.4, and in the figures 5.1 to 5.4. In these figures, the calculated value is compared with the observed values.

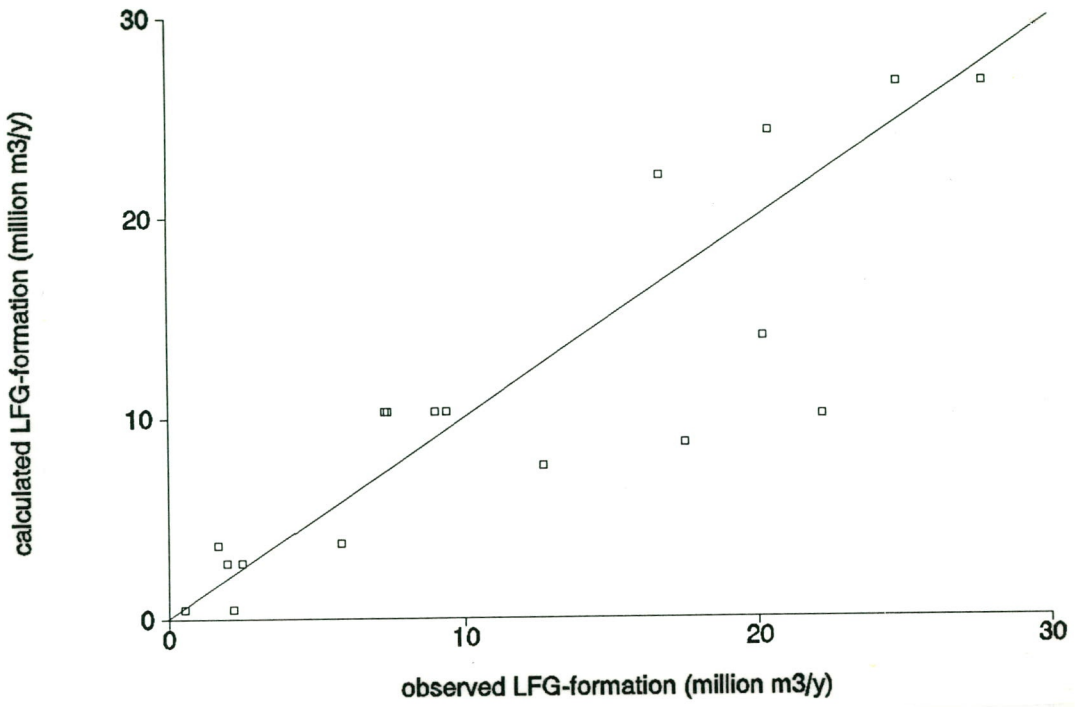

Figure 5.1 Observed and calculated landfill gas formation with the zero order model

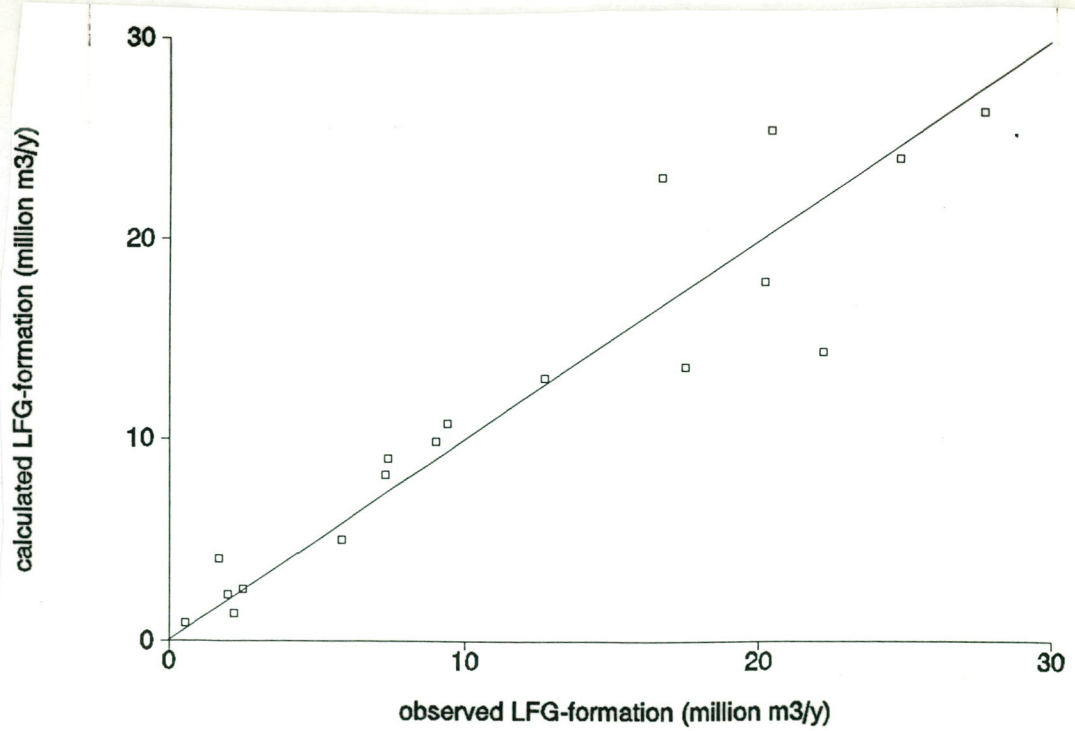

Figure 5.2 Observed and calculated landfill gas formation with the first order model

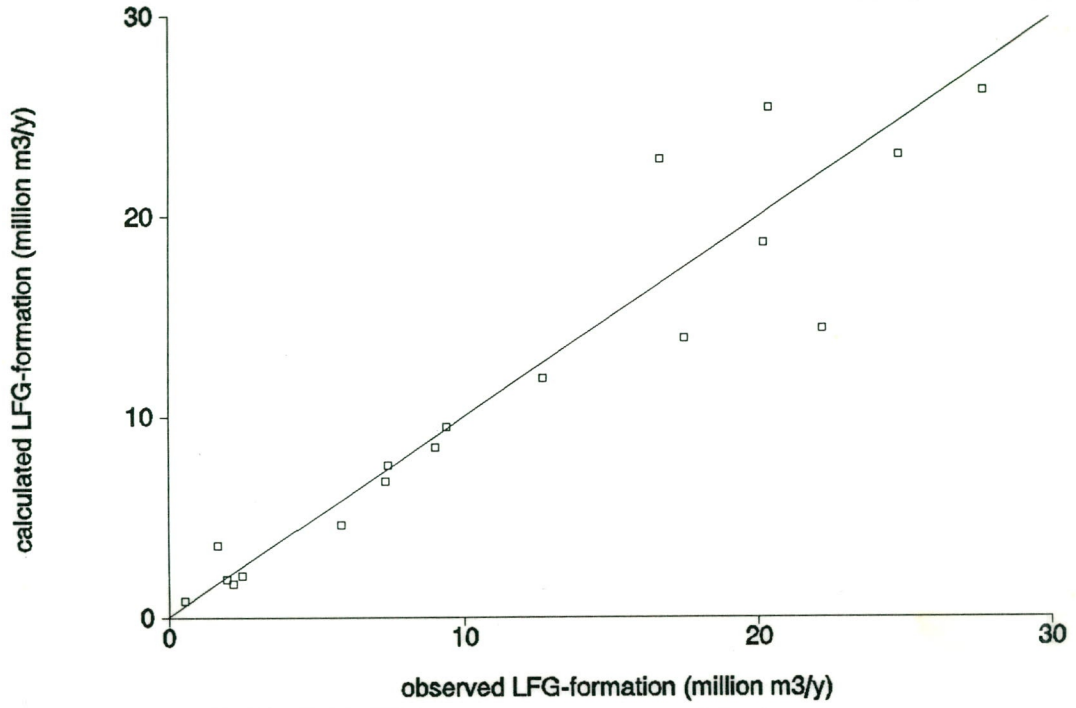

Figure 5.3 Observed and calculated landfill gas formation with the multi-phase model

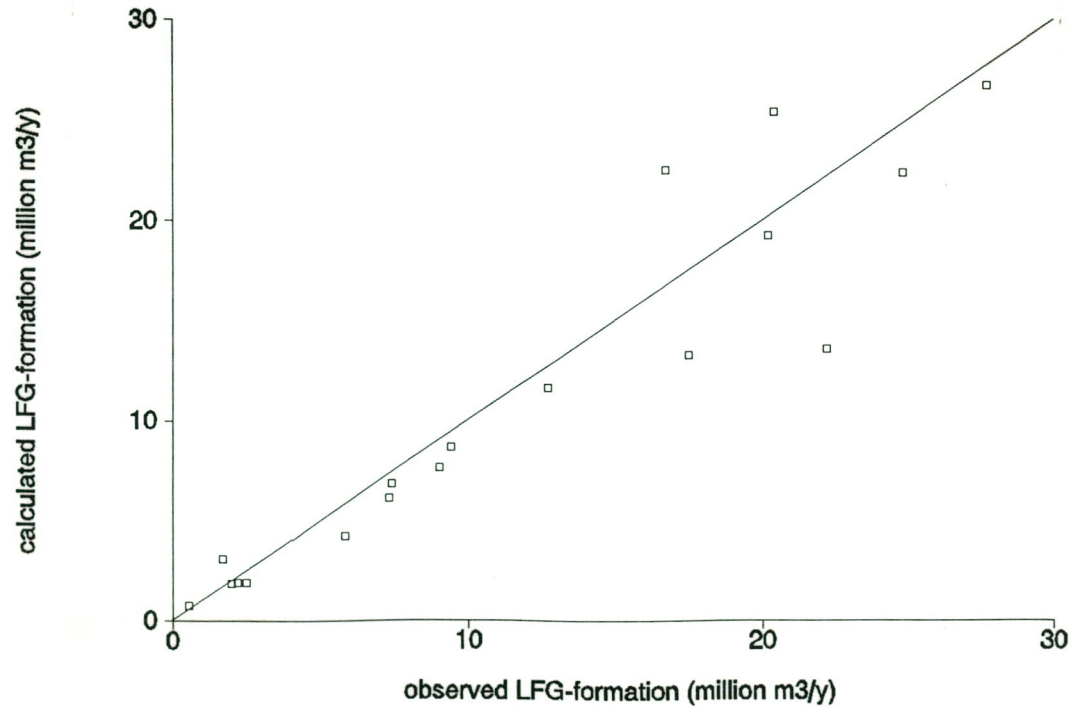

Figure 5.4 Observed and calculated landfill gas formation with the second order model

6 Discussion

Predictability of landfill gas formation
The errors in the observed landfill gas formation, relative to the calculated ones are depicted in figure 6.1. In this figure is presented how many predictions were within the error range of 1 to 10%, how many in the range 11-20% and so on. Mean relative errors are listed in table 6.1.
In general, models are more accurate than previously expected (the 50%, as previously mentioned). This is even more remarkable when one considers, that the data-set contained landfills with relatively very low (e.g., Hardenberg) and surprisingly high gas recovery (e.g., Schijndel).

Table 6.1 Mean relative errors

Model	Mean relative error
zero-order	44%
first-order	22%
multi-phase	18%
second-order	22%

Comparison of the models
When the models are ranked for their ability to describe landfill gas formation, the result is not very surprising. The zero-order model being the most unreliable, the first order model and the second order model being almost comparable, and the multi-phase model yielding the best results.
However, the difference between the latter three models is very small.
The difference between the first-order and the multi-phase model is most likely not connected to the nature of the multi-phase model (in the first years rapid decomposition of the fast degradables; a relative high gas production at the end, due to the high content of slow degradables).
Most likely the difference between the first-order model and the multi-phase model is due to the number of model-parameters: a four-parameter fit will always outdo a two-parameter fit.
As a result of this, although the multi-phase models provides a better description of observed formation, landfill gas formations, predicted with this model are not necessarily superior to predictions with the first order model.

Sources of discrepancies between calculated and observed formation
As stated before, there are four possible reasons for a difference between calculated and observed landfill gas formation:
- the estimates of the recovery efficiency are not accurately known;
- the amount of waste and waste compositions are not accurately known;
- there is an inherent variation in landfill gas formation, caused by the inhomogeneity of the landfill, presence of inhibitors or nutrients and other more or less fortituous factors;
- the models give no good representation of landfill gas formation.

The fact that hardly any distinction can be made between the models, and that numerous sets of model parameters are equivalent in the case of the multi-phase model, indicates that the models describe landfill gas formation rather well, and that deviations between observed and calculated formation are most likely caused by the other three errors.

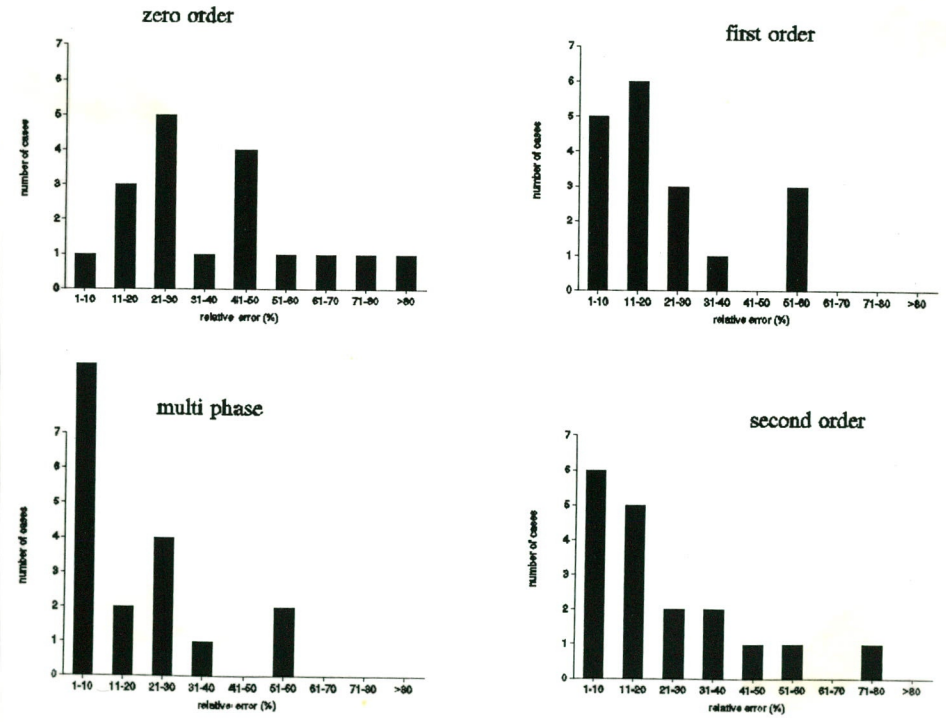

Figure 6.1

7 Conclusions

- In a validation of landfill gas formation models in seventeen cases, distributed over nine Dutch landfills, landfill gas formation could be fairly well modelled using the models tabulated in table 3.1. The majority of results with a relative error of less than 30%.

- Optimum model parameters are:

Table 7.1 Landfill gas formation models

– Zero order model	$\alpha_t = \zeta 1.87 \times k_0 A$	$\zeta\, k_0 = 2.4$ kg tonne^{-1} y^{-1}
– First order model	$\alpha_t = \zeta 1,87 A C_0 k_1 \times e^{-k_1 t}$	$\zeta = 0.58$ $k_1 = 0.094$ y^{-1}
– Multi-phase model	$\alpha_t = \zeta \sum_{j=1}^{3} 1.87 A C_{0,i} k_{1,i} \times e^{-k_{1,i} t}$	$\zeta = 0.58$ $k_{1,1} = 0.185$ y^{-1}; $k_{1,2} = 0.100$ y^{-1} $k_{1,3} = 0.003$ y^{-1}
– Second order model	$\alpha_t = \zeta 1.87 A k_2 \left(\frac{C_0}{k_2 C_o t + 1} \right)^2$	$\zeta = 0.64$ $k_2 = 0.0012$ tonne kg^{-1} y^{-1}

In this table α_t is the landfill gas formation in m^3 per year, ζ is the generation factor, k_n are model parameters, A is the amount of waste in place in tonnes; C_0 and $C_{0,i}$ are the amount of organic carbon in the waste and the amount of organic carbon of a specific fraction in kg per tonne, respectively; t is the time in years, elapsed since the depositing of the waste; the factor 1.87 has the dimension m^3 per kg.

- Description of landfill gas formation improves ongoing from the zero-order model to the first and second order model to the muli-phase model.

- The predictive value of the multi-phase model and the first-order model are about equal.

- Models describe landfill gas formation rather well. Deviations between observed and calculated landfill gas formation are more connected to other aspects like uncertainties in amounts of waste and recovery efficiencies.

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Appendix 1 Amounts of waste

The amounts of waste presented in this appendix refer to the waste, in which gas was recovered in the years in which landfill gas formation was estimated. So these amounts do not necessarily match the total amounts of waste in place.

Table A1.1 Amounts of waste in Ambt-Delden (in tonne)

Year	Domestic[1] waste	Industrial[2] waste
1970	98250	32750
1971	98250	32750
1972	98250	32750
1973	111750	37250
1974	102750	34250
1975	122250	40750
1976	46500	15500
1977	100500	33500
1978	119250	39750
1979	134250	44750
1980	107250	35750
1981	105750	35250
1982	105750	35250
1983	105750	35250
1984	112500	37500
1985	112500	37500
1986	56250	18750

1) total waste is assumed to contain 75% of domestic waste
2) total waste is assumed to contain 25% of industrial waste

Table A1.2 Amounts of waste in Bavel (in tonne)[1)]

Year	Domestic waste	Industrial waste	Demolition waste	Sludge	Agricultural waste
1968	37689	21380,7	30731,3	6479	
1969	41374	28096,2	40295,8	8514	
1970	42086	24901,8	35746,2	7546	
1971	44565	28066,5	40253,5	8505	
1972	49870	26301	37739	7970	
1973	56058	34115,4	48868,6	10338	
1974	61806	37837,8	54170,2	11466	
1975	70297	50612,1	72363,9	15337	
1976	76470	53270	76720	16350	
1977	80420	99330	40840	19810	
1978	87160	120080	52550	27460	
1979	135520	63310	70700	26630	
1980	139620	72770	42720	26950	
1981	133790	60450	29580	30540	
1982	137425	23050	16175	11350	1400
1983	125125	11800	18150	9925	1300
1984	121350	26125	22150	11300	850
1985	172660	30590	23275	15790	4740
1986	164500	22600	33500	34600	1300
1987	206400	23600	47400	34700	3100
1988	198530	25900	93300	34495	1800
1989	207575	30100	74000	40900	500
1990	224838	29377	84914	49006	8077
1991	218554	47050	125444	34811	9345
1992	218554	47050	125444	34811	9345

1) Medio 1991 gas was recovered from the waste, dumped until June 1990 (in this report referred to as Bavel1); medio 1992 gas was recovered from the waste dumped until August 1991 (in this report referred to as Bavel2); After Februari 1993 gas was recovered from all the waste (in this reprt referred to as Bavel3).

Table A1.3 Amounts of waste in Hardenberg-Collendoorn (in tonne)

Year	Domestic waste	Industrial waste
1974	13320	3996
1975	18000	5400
1976	21240	6372
1977	21000	6300
1978	30000	9000
1979	62640	18792
1980	69900	20970
1981	61260	18378
1982	52500	15750
1983	52740	15822
1984	54000	16200
1985	54000	16200
1986	54000	16200
1987	54000	16200
1988	20000	5000

Table A1.4 Amounts of waste in Hengelo (in tonne)

Year	Domestic waste	Industrial waste	Demolition waste
1985	3152	7632	4652
1986	193587	46461	40792
1987	265386	58932	50814
1988	124968	30692	19144

Table A1.5 Amounts of waste in Schijndel (in tonne)

Year	Domestic waste	Industrial waste
1977	87014	
1978	105720	
1979	111720	
1980	120800	
1981	125722	
1982	120328	
1983	120089	
1984	119968	
1985	122658	
1986	122998	
1987	131720	
1988	133037	
1989	140000	70000
1990	139000	73000
1991	152000	51000
1992	158000	53000

Table A1.6 Amounts of waste in Schinnen (in tonne)

Year	Domestic waste	Sludge	Demolition waste	Composting residues
1973	75842	1207	7441	
1974	78876	1255	7739	
1975	82031	1306	8049	
1976	85313	1358	8371	
1977	88726	1412	8705	
1978	92274	1469	9054	
1979	95966	1527	9416	
1980	99803	1589	9792	
1981	105287	1652	10184	
1982	107948	1718	10592	
1983	112266	1787	11015	
1984	111930	2029	10903	
1985	106482	8775	10298	
1986	111607	17854	10879	
1987	127386	14920	10226	
1988	144682	26642	42244	
1989	168343	39066	41298	
1990	177024		4149	
1991	316085		4305	
1992	284856		4314	9960
1993	186579		2878	8277

Table A1.7 Amounts of waste in Stainkoel'n (in tonne)

Year	Domestic waste
1986	76000
1987	44000

Table A1.8 Amounts of waste in Vasse (in tonne)

Year	Domestic waste	Industrial waste
1975	11773	1500
1976	25881	15000
1977	42796	30000
1978	47265	30000
1979	56419	31357
1980	43667	47318
1981	52211	39420
1982	53000	39000
1983	33718	19658
1984	9151	273

Table A1.9 Amounts of waste in Veendam (in tonne)[1)]

Year	Domestic waste	Industrial waste	Agricultural waste	Sludge
1976	20000			
1977	30000			
1978	36000			
1979	37000			
1980	38000			
1981	39000			
1982	40000	30000	3000	
1983	60000	50000	5000	
1984	65000	55000	5000	
1985	73000	58000	11000	
1986	74000	74000	9000	
1987	86000	70000	14000	
1988	83069	70118	13381	2756
1989	83623	68430	12769	2499
1990	85062	63843	14989	1336
1991	86135	60519	11735	1344
1992	62490	75691	15204	2279
1993	61866	74934	15052	2256

1) Februari 1994 gas was recovered from the waste, dumped until June 1992 (in this report referred to as Veendam1); medio 1994 gas was recovered from all the waste (in this reprt referred to as Veendam2).