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UNCERTAINTY ASSESMENT OF MODELS FOR LANDFILL BIOGAS PRODUCTION

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Abstract *This paper deals with models for landfill gas production and its combinations. An IPCC (Intergovernmental panel on climate change) 1st order model is accessed, combined to auxiliary equations from literature. Data from an actual landfill is used to feed the model and then analyze its capacity to predict biogas production, parameter sensibility and combined uncertainties. The modified model predicts the Landfill gas (LFG) production and shows an inflection on its curve at the same time that the waste disposal changed, indicating its coherency. The LFG combined uncertainty is estimated to be around +/- 50% of the nominal model output, within 68% probability. The use of maximum and minimum values of the key parameters (DOC and k) as a way to roughly explore the model uncertainties, instead of a proper combined propagation, showed to be acceptable depending on the DOC model calculation. The assessment carried out in this study allows identifying the importance of the proper determination of gas generation parameters to estimate landfill gas generation, which is critical for decision-making in LFGE projects.*

Keywords: *Landfill gas to energy; municipal solid waste; landfill energy modeling; waste to energy*

1. INTRODUCTION

Landfills are the third largest anthropogenic source of methane; therefore. recovery of landfill gas is a critical component of integrated solid waste management, and landfill gas energy (LFGE) utilization is expected in advanced solid waste management systems (Economopoulos. 2012; Global Methane Initiative, 2012).

They remain widely accepted in many countries as a final destination of solid waste (SW) due to their economic advantages (Renou et al., 2008). The two major landfill effluents are gas emissions, called landfill gas – LFG, and a liquid stream called leachate. LFG is a mixture of methane with other gases as a result of a biodegradation process. It is burning without any energy recovery is a common practice to mitigate its potential greenhouse gas effects. According to IPCC (2006) landfills are responsible to 3 – 4% of the global greenhouse gas emissions.

Brazil is the third largest country in total municipal solid waste generation. with 149.096 tonnes per day (Hoornweg and Bhada-Tata, 2012). The 2010 Brazilian National Solid Waste Policy established the energetic utilization of landfill gas and called states to set LFGE utilization goals, with an overall 311 MW projected capacity (MME. 2012).

Although landfill is a final deposition site for solid waste, its effluents can be considered as renewable sources. LFG can be burnt on heaters, boilers and combustion engines with heat or electrical conversion. Leachate is usually sent to urban effluent treatment units, where different technologies are employed to neutralize its pollutant content. Its residual organic content suits to be burned and offers again a possibility for energy conversion.

The present study assesses the potential of landfill gas production applied to an actual landfill facility, and focus on the assessment of the model sensibility and combined uncertainties.

2. LFG GENERATION MODELING

The simplest models for LFG generation presented in the literature are of zero, first and second-orders, based on empirical data (Amini *et al.*, 2012). Results depend strongly on the quality and accuracy of the input data and on the approximation of the model assumptions to the landfill real conditions, such as the waste decomposition rate and anaerobic conditions. Oonk and Boom (1995) performed assessments with these approaches and compared them to measured data from Netherlands landfills. They found that the zero order models were unable to reproduce LFG generation and that the second order model presented more accurate results than the first order model, but such gain in accuracy demanded more complex data, which sometimes may not be justified.

Among the most widely used first order decay models, the one from IPCC (2006) allows the prediction of LFG production rate based on methanogenesis phase behavior. One key factor in this model is the degradable organic carbon *DOC* (Gg of organic carbon/Gg of total solid waste) which is normally taken from IPCC model, but it was calculated in the present work by the expression from Machado et al. 2009, as follows:

$$DOC = \frac{\rho_{CH_4}}{F_{CH_4} MW_{Ratio} DOC_f MCF}\left(\frac{BF}{(1+w)}\frac{C_m}{10^3}\right) \quad (1)$$

where ρ_{CH4} is the CH_4 density (kg/m³) at standard temperature and pressure (0°C and 101.325 kPa). F_{CH4} is the LFG methane volumetric fraction, MW_{Ratio} is the molecular weight ratio of CH_4 to C, *MCF* is the methane correction factor that takes into account the disposing practices in solid waste sites, ranging from 0.4 for unmanaged sites to 1 for controlled landfills, DOC_f indicates the fraction of *DOC* that is supposed to undergo anaerobic reactions, *BF* is the biodegradable fraction in SW (dimensionless), C_m is the maximum value of methane produced by a certain amount of waste (Nm^3 CH_4/ ton of SW) and *w* is the moisture content of MSW (dimensionless).

The IPCC methodology was retrieved from this point on, by calculating the degradable organic carbon *DDOCm* (Gg) for a specific waste component *i*, as follows:

$$(DDOC_m)_i = (W\ FR_i)\, DOC_i\, DOC_f\ MCF \quad (2)$$

where *W* is the waste mass (Gg) FR_i is the fraction of each component in the total waste mass, obtained from gravimetric analysis. Equation (3) expresses the rate of degradable organic carbon *DDOCm*, in Gg of organic carbon per second as:

$$\frac{d[DDOC_m]}{dt} = -k(DDOC_m) \quad (3)$$

where *k* is the reaction rate constant (year^{-1}), a half-life value defined as the necessary time for the mass of available organic matter to decay to half of its initial value. Its evaluation relies on the waste density, pH, depth, composition, climatic conditions and other landfill and environmental conditions (Amini et al., 2012; Machado et al., 2009; Penteado et al., 2012), and can be estimated as an overall value or for specific waste components. Its solution leads to the expression of the decomposable degradable organic carbon *DDOCm(t)* as a function of time *t*, as:

$$DDOC_m(t) = DDOC_m(0)\,(e^{-k\,t}) \quad (4)$$

where $DDOC_m(0)$ is the initial value of $DDOC_m$. In order to evaluate LFG generation, Eq. (5) may be rewritten for $DDOCm_{dec\ T}$, which is the amount of *DDOCm* at end of an inventory year *T*:

$$(DDOC_{m\,dec})_T = \left[(DDOC_{m(T-1)}) + (DDOC_{ma})\right]\left(1 - e^{-k_i}\right) \quad (5)$$

with $DDOCm_{(T-1)}$ the amount of $DDOC_m$ (Gg of organic carbon) disposed in the year prior to inventory year *T* and $DDOCm_a$ the amount of $DDOC_m$ that was not decomposed in the years before *T*-1.

The mass of generated methane for the inventory year *T*, $CH_{4g\ T}$ (Gg), was determined in the present work as:

$$CH_{4g} = F_{CH_4} MW_{Ratio} \sum_{i=1}^{z} (DDOC_{m\,dec})_i \quad (6)$$

with *z* the number of waste components.

Finally, the average annual volumetric flow rate of LFG generated over the year *T*, $LFG_{a\ T}$ (Nm^3/h), is given by

$$LFG_a = \left(\frac{CH_{4g}}{\Delta h_{year}\, 10^6}\right)\left[\frac{1}{\rho_{CH_4}} + \left(\frac{MW_{CO_2}}{MW_{CH_4}}\frac{1}{\rho_{CO_2}}\right)\left(\frac{1 - F_{CH_4}}{F_{CH_4}}\right)\right] \quad (7)$$

where ρ_{CO2} is the CO_2 density (kg/m³) at standard temperature and pressure (0°C and 101.325 kPa). MW_{CO2} and MW_{CH4} are the molecular weights of CO_2 and CH_4 (kg/kmol) and $\Delta hour_{year}$ is the number of hours per year (8.760 h). Equation (8) describes the average annual volumetric flow rate of LFG recovered over the year *T*, $LFG_{a\,T}^{R}$ in Nm³/h, where η_c is the efficiency of the extraction system:

$$LFG^{R}{}_{aT} = \eta_c \; LFG_{\;aT} \tag{8}$$

The amount of available *LFG* for energetic conversion can be estimated upon landfill historical records and the efficiency of the extraction system η_c. These parameters may be obtained throughout distinct methodologies, such as theoretical prediction, laboratory essays or best-fit analysis of collected gas of an existent landfill (Amini et al., 2012; Machado et al., 2009). Calculation sequence is depicted in Fig. (1).

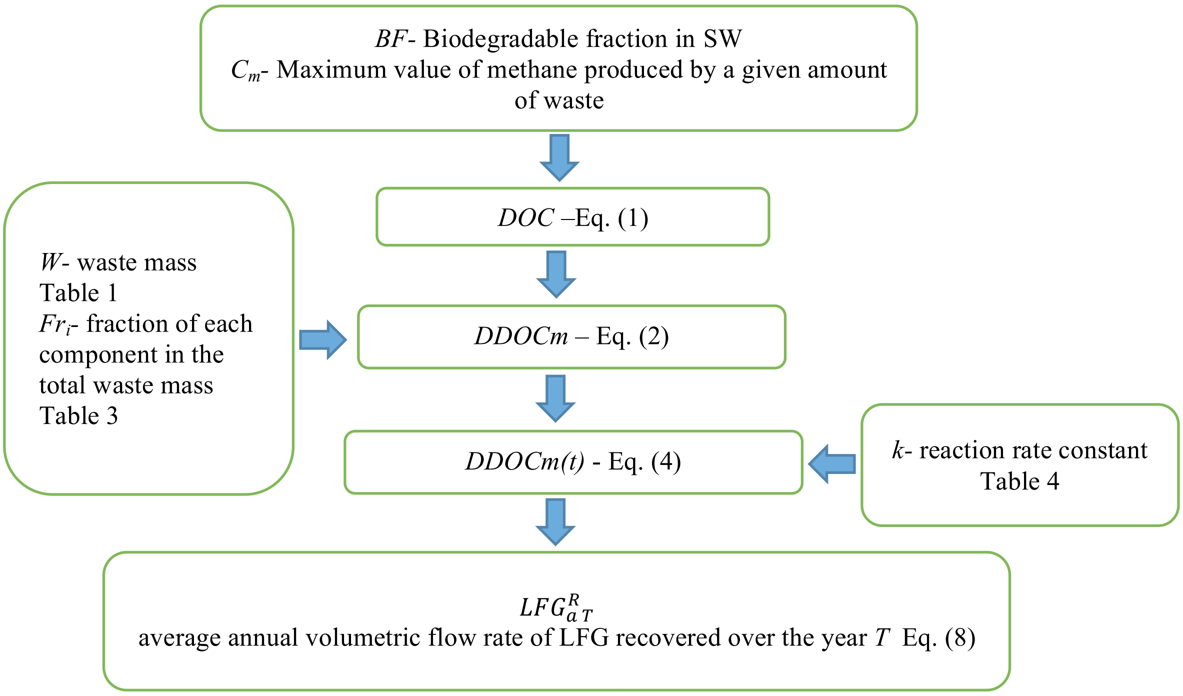

Figure 1. Flowchart of the IPCC (2006) 1st order model for LFG estimation.

3 CASE STUDY: THE GUAJUVIRAS LANDFILL

Data from the Guajuviras landfill were chosen as input to the IPCC model. This landfill is located in Canoas, a 300 thousand inhabitants town in south Brazil, and was initially created as an open dump for municipal solid waste disposal. It became a landfill after January 1996 to be finally closed in December 2011. With a landfilling area of 81.000 m², topsoil, intermediate and bottom layers made of 0.6 m compacted clay, it received more than a million tons along its lifetime operation (Table 1).

Table 1: Municipal solid waste disposed in the Guajuviras landfill per year

Year	1996	1997	1998	1999	2000	2001	2002	2003
MSW in ton	48,896.03	51,732.87	56,913.31	60,146.37	58,231.67	59,916.16	58,087.28	61,782.26
Year	2004	2005	2006	2007	2008	2009	2010	2011
MSW in ton	64,471.73	74,372.59	72,576.69	75,952.07	79,993.90	78,278.46	78,066.87	81,594.67

The solid waste gravimetric composition was assumed to be similar to the one from the neighbor city of Porto Alegre, due to the lack of information on the original site: 57.27% organic matter; 26.8% inert; 11.62% paper/cardboard; 3.86% textiles; 0.45% wood in wet basis (PMPA, 2013). The organic matter content refers to food and yard waste, but there was no record about the weight of these two fractions. In the present study, organic matter was considered as composed only by food.

Guajuviras LFG production was estimated by applying IPPC 1st order method (Fig. (1)), starting with parameters *BF* and C_m, collected from literature and presented as follows:

Table 2 –Literature values for *BF*, the biodegradable fraction in solid waste, and *Cm*, the maximum value of methane produced by a certain amount of waste (Nm³ CH4/ ton of SW)

	Source	Paper	Paperboard	Food	Wood	Textile
BF (dimensionless)	Tchobanoglous et al. (1993)	0.44	0.38	0.58	0.61	0.4
	Barlaz et al. (1997)	0.19-0.56	0.39	0.7	0.14	-
	Harries et al. (2001)	0.30-0.40	0.44	-	0.3-0.33	0.17-0.25
	Lobo (2003)	0.40	0.64	0.64	0.17	0.32
	Average	0.39	0.46	0.64	0.03	0.30
	Dispersion	0.038	0.12	0.06	0.21	0.09
C_m (Nm³ CH4/ton)	Cho et al. 2012)	-	410	643	487	509
	Tchobanoglous et al. (1993)	418.51	438.70	505.01	484.72	573.87
	Average	418.51	424.35	574.01	485.86	541.44
	Dispersion	-	20.29	97.57	1.61	45.87

BF and Cm average values led to the estimation of the average DOC_i, per waste component Eq. (1). The component fraction *Fr* was taken from the gravimetric collection for the nearby city of Porto Alegre (PMPA, 2012), in % in humid base, with 11.62% paper/paperboard, 57.27% organic matter (food and yard waste), 0.45% wood, 3.86% textile, 16.19% inert and 10.61% others.

Landfill climate zone classification was assumed to calculate k as a function of the annual accumulated precipitation and the environmental mean annual temperature. Climate data were taken from the nearest meteorological station, at Porto Alegre, due to the lack of available data. Its accumulated annual precipitation was higher than 1,000 mm and the mean annual temperature was around 20°C. The border values of the reaction rate constant, $k_{i\ max}$ and $k_{i\ min}$, were taken from IPCC (2006) suggested values for wet temperate climate zone, and displayed in Table 3.

Table 3. Reaction rate constant k (year^{-1}) suggested by IPCC (2006)

k (year^{-1})	Paper/Paperboard	Organic matter	Wood	Textile
$k_{i\ max}$	0.07	0.20	0.04	0.07
$k_{i\ min}$	0.05	0.10	0.02	0.05
Average	0.06	0.15	0.03	0.06
Dispersion	0.01	0.08	0.01	0.01

The average values of k fed Eq. (4) and a straight forward calculation led to the estimation of $LFG^R_{a\,T}$, the average annual volumetric flow rate of LFG recovered over the year *T,* Eq. (8), displayed in the next figure.

The LFG pick was predicted to happen around the year 2012, when actually the waste disposal was ceased. From that point on, an expected decay of its production was estimated, till the extinction of the landfill activities in 2045.

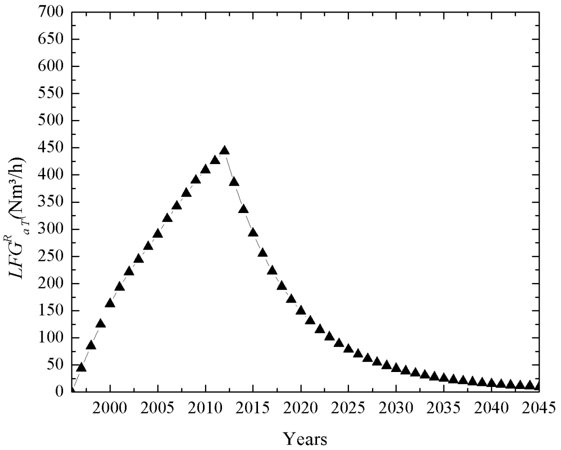

Figure 2. Estimated value of $LFG^R_{a\,T}$, in Nm3/year, the LFG average annual volumetric flow rate recovered over year T

4 MODEL UNCERTAINTIES

The uncertainties associated to the estimated value of $LFG_{a\,T}^{R}$ were accessed in order to define a range that borders its true value within a given probability. The model sensibility to its inputs was first calculated, in order to reduce the computational effort of uncertainty propagation that was then performed.

Sensibility evaluation was performed by a one to one ±10% parametric variation over the model input data. The eight selected parameters are presented in the next table, followed by the correspondent LFG production for the selected year of 2012.

Table 4. LFG individual sensibility to model parameters and its minimum and maximum relative bias. Data from 2012, the highest predicted production year (*LFG* = 443.47 Gg).

Input	LFG production for 2012 (Gg) Min	Max	LFG relative bias *Rb*	
	-10%	10%	Rb_{Min}	Rb_{Max}
BF	399.13	479.06	10.00	8.03
Cm	399.13	479.06	10.00	8.03
W	431.51	459.40	2.70	3.59
Fr	399.13	487.82	10.00	10.00
k	426.73	468.16	3.77	5.57
MCF	443.47	443.47	0.00	0.00
DOCf	443.47	443.47	0.00	0.00
FCH4	443.33	443.62	0.03	0.03

The minimum and maximum relative bias Rb_{min} and Rb_{max} were calculated after the following relations:

$$Rb_{min} = \frac{LFG_{average} - LFG_{-10\%}}{LFG_{average}}\, 100 \quad \text{and} \quad Rb_{max} = \frac{LFG_{+10\%} - LFG_{average}}{LFG_{average}}\, 100 \tag{9}$$

The approach following Eq (9) showed that the *LFG* production was most sensitive to variations in *BF*, C_m and *Fr* in the first place, followed secondarily by *k*. This exploratory study allows to disregard the influence of *w*, *MCF,* DOC_f and *FCH4* in the composition of the combined uncertainties because these terms, especially *MCF* e DOC_f are canceled when DOC estimation (Eq. (1)) is replaced in the $DDOC_m$ estimation (Eq. (2))

The uncertainty u_{LFG} associated to the average annual volumetric flow rate of LFG recovered over a given year *T* , $LFG_{a\,T}^{R}$ in Eq. (8), was calculated by the following propagation expression (Cabral, 2004),

$$u_{LFG}^2 = \sum_{i=1}^{n} \left[\frac{\partial\, LFG}{\partial x_i}\right]^2 u{x_i}^2 + 2\sum_{i=1}^{n-1}\sum_{j\neq i}^{n} \frac{\partial\, LFG}{\partial x_i}\frac{\partial\, LFG}{\partial x_j} u_i u_j\, u_{ij}. \tag{10}$$

where x_i stands for the model parameters and ux_i their associated uncertainties. The number of *i* parameters was limited to four (*n*=4), as a result of the sensibility evaluation, and the index *j* referred to the cross product. Parameter average values are presented in the next table, followed by its dispersion, assumed to be the parameter uncertainty ux_i.

Table 5. Average and uncertainties of the input data for LFG production model

	k		*BF*		*Cm*		*Fr*	
Waste	Average	u_k	Average	u_{BF}	Average	u_{Cm}	Average	u_{Fr}
Paper/Paperboard	6,00E-02	1,00E-02	4,27E-01	9,15E-02	4,22E+02	1,47E+01	1,16E-01	3,49E-02
Organic matter	1,50E-01	8,50E-02	6,40E-01	6,00E-02	5,74E+02	9,76E+01	5,73E-01	1,72E-01
Wood	3,00E-02	1,00E-02	3,09E-01	2,15E-01	4,86E+02	1,61E+00	4,50E-03	1,35E-03
Textile	6,00E-02	1,00E-02	6,00E-02	1,00E-02	6,00E-02	1,00E-02	3,86E-02	1,16E-02

Uncertainties for *k, BF* and *Cm* were collected from tables 2 and 3, except for *Fr*, which is an exact value. An uncertainty of 30% was adopted for this parameter, following IPCC (2006) recommendation. In order to be conservative, all these uncertainties were associated to a unitary standard deviation, and results are displayed in the next figure.

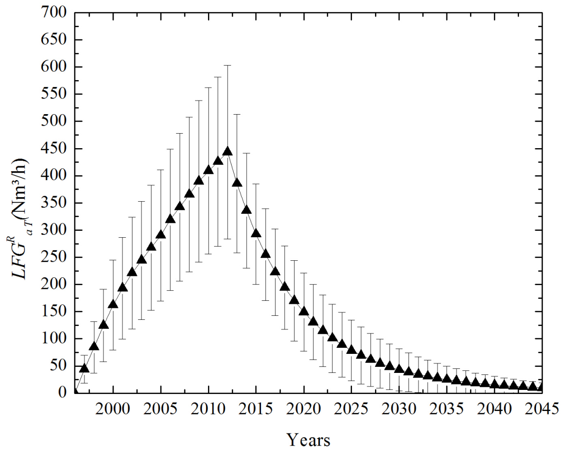

Figure 3. Combined uncertainty associated to the estimated value of LFG^R_{aT}, in Nm3/year, the average annual volumetric flow rate of *LFG* recovered over the year *T*

The uncertainty increased in absolute value together with the *LFG* production, and reached its maximum around the year of 2012. Waste disposal finished in 2012, and both the model prediction and uncertainty decreased steadily. The reaction coefficient *k* became the model key parameter because *BF*, C_m and *Fr* vanished after the end of the landfill activities, from 2013 to 2045.

The product of the most sensitive parameters times their correspondent uncertainties allowed to identify the individual impact on the overall uncertainty of the landfill gas production, as shown in the following table.

Table 6. Landfill gas combined uncertainty for 2012 (*LFG* = 443.47 Gg).

Waste	X_i	$\left[\frac{\partial\ LFG}{\partial X_i}\right]^2$	$uX_i{}^2$	$\left[\frac{\partial\ LFG}{\partial X_i}\right]^2\ u_i{}^2$
Paper/Paperboard	*BF*	5,78E+01	8,37E-03	7,00E+00
	C_m	8,54E-04	2,17E+02	1,86E-01
	Fr	1,13E+04	1,22E-03	**1,37E+01**
	k	3,98E+04	1,00E-04	3,98E+00
Organic Matter	*BF*	1,01E+05	3,60E-03	3,65E+02
	C_m	1,26E-01	9,52E+03	1,20E+03
	Fr	1,26E+05	2,95E-02	3,72E+03
	k	1,59E+06	7,23E-03	**1,15E+04**
Wood	*BF*	3,91E-01	4,62E-02	**1,81E-02**
	C_m	1,58E-07	2,17E+02	3,43E-05
	Fr	1,84E+03	1,82E-06	3,35E-03
	k	4,02E+01	1,00E-04	4,02E-03
Textile	*BF*	1,27E+02	9,10E-03	**1,16E+00**
	C_m	4,17E-05	2,10E+03	8,78E-02
	Fr	8,21E+03	1,34E-04	1,10E+00
	k	3,20E+03	1,00E-04	3,20E-01

The right column in Table 6 points out the most relevant parameters are *Fr* for paper/paperboard, the *k* reaction rate for organic matter and *BF* for both wood and textile waste.

The use of this 1st order method can be a challenge for regular landfill designers, and the calculation of the combined uncertainties becomes out of their scope. Nevertheless, it is quite common to try to find borders for models by combining the extreme values of its inputs. Predictions can be seen as fairly impossible to happen, but the procedure gives at least an aid to the decision processes of energy valorization or exhaust system design. Following this path, the range of uncertainties was estimated by assuming two extreme scenarios: skeptical and optimistic.

Calculations were performed in respect to the reaction rate constant k_i (Table 3) and the ratio of organic carbon to the solid waste total amount DOC_i (Eq. (1)), as shown in Figure 4. This ratio brings together parameters as *BF*, C_m and *Fr*, rated as the most sensible from the model point of view, as seen before.

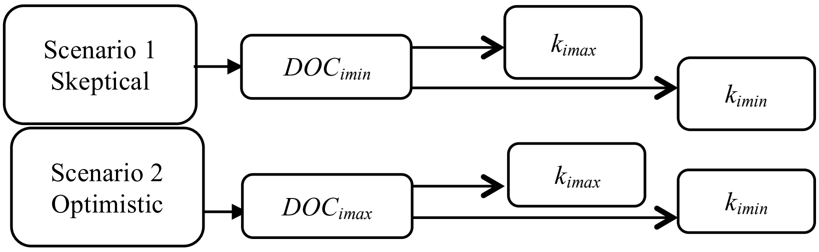

Figure 4. Scenario assembling for *LFG* generation

Two approaches were used to estimate the extreme values of DOC_i: the first one come from IPCC (2006) data, referred here as DOC_i^{IPCC}, and the second one was based on the methodology adapted from Machado et al. (2009), with extreme input data *BF* e C_m, referred here as $DOC_i^{BF-C_m}$. Next table brings *DOC* values calculated after these two approaches, followed by its relative deviations.

Table 7. Average and extreme values of the ratio of organic carbon to the solid waste total amount obtained from DOC_i^{IPCC} and $DOC_i^{BF-C_m}$ in Gg organic carbon/Gg total waste and their relative deviations in %

MSW components	$\overline{DOC}_{i,av}^{IPCC}$	$DOC_{i,min}^{IPCC}$	$DOC_{i,max}^{IPCC}$	RD^{IPCC}	$\overline{DOC}_{i,av}^{BF-C_m}$	$DOC_{i,min}^{BF-C_m}$	$DOC_{i,max}^{BF-C_m}$	RD^{BF-C_m}
Paper/Paperboard	0.405	0.36	0.45	+/- 11.11	0.35	0.15	0.55	+/- 57.14
Organic matter	0.14	0.08	0.20	+/- 42.86	0.5	0.39	0.61	+/- 22.00
Wood	0.425	0.39	0.46	+/- 8.24	0.345	0.13	0.56	+/- 62.32
Textiles	0.3	0.20	0.40	+/- 33.33	0.285	0.16	0.41	+/- 43.86

RD = Relative Deviation, calculated by (Average DOC_i – $DOC_{i,min\ or\ max}$)/ Average DOC_i
W values from Table 1; *DOCf* = 0.5 (IPCC, 2006); gravimetric composition from Porto Alegre; η_c=20%; F_{CH4} = 0.5; *MCF*=1.

Results for the average value of DOC_i, displayed as $\overline{DOC}_{av}$, were different according to the calculation methodology for each of the MSW component, and in particular in respect to organic matter, the main LFG agent. The underlined values refer to the extreme values of DOC_i calculated by both IPPC and $BF + C_m$ input data input data. The first one generated only one single extreme value, the one for organic matter, whereas the use of $BF + C_m$ input data was responsible for all extreme values.

Figure 5 presents the recovered average annual volumetric flow rate in *T* - $LFG_{a\,T}^R$, calculated after these extreme scenarios. Results from Eq. (8), together with their combined uncertainties, were followed by the calculations performed after the two scenarios. DOC_i was taken form the underlined values of Table 8 and associated to the minimum and maximum values of k_i, displayed in Table 3.

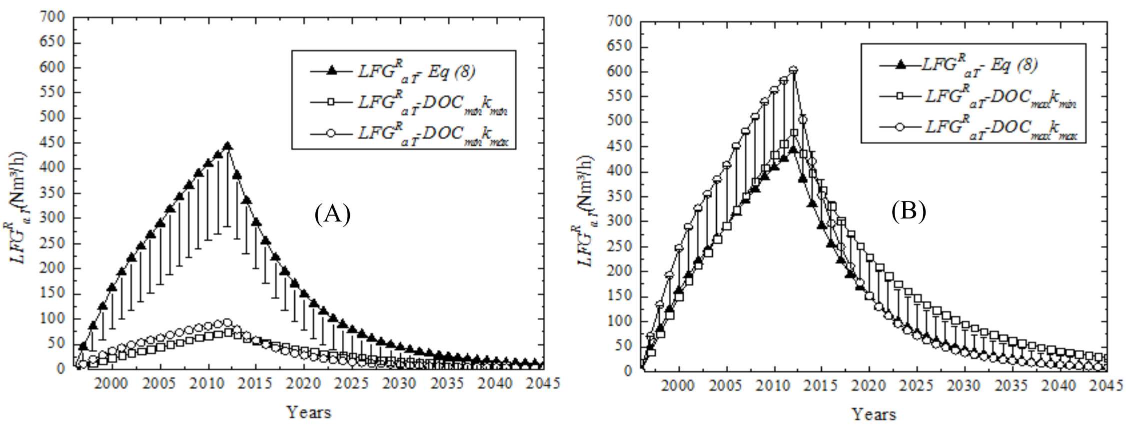

Figure 5: Recovered landfill gas average annual volumetric flow rate in T -$LFG_{a\,T}^R$, calculated after Eq. (8) and bordered by (A) Skeptical scenario and (B) Optimistic scenario

The analysis of curves for extreme scenarios shows that DOC_i performs a prominent role in comparison to k_i. For the same value of k_i, there was a difference on the $LFG_{a\,T}^R$ response of five to six times, by varying DOC_i. In the other hand, results for $LFG_{a\,T}^R$ were only one to two times higher by varying k_i for a a constant value of DOC_i.

The outcomes for the skeptical scenario were of 74 Nm^3/m with k_{min} and 93 Nm^3/m with k_{max}, far below the average value of 479 Nm^3/h and its uncertainty range. This indicates an underestimation in the generation of LFG, mainly due to the use of $DOC_{i,min}^{IPCC}$. The optimistic scenario generated more forthcoming evaluations of the biogas production uncertainty.

6. CONCLUSION

Landfill gas production *LFG* was predicted by a 1st order model recommended by IPCC, 2006, and the sensibility and uncertainties of its outputs were accessed. The present work dealt with 2 calculation options for the key parameter *DOC*, the degradable organic carbon, found in IPCC, 2006, and Machado et al., 2009, witch lead to significant differences on the overall results and their uncertainties. The 1st order model with *DOC* calculation after Machado et al., 2009, predicted the *LFG* production and showed an inflection on its curve at the same time that the waste disposal was closed, witch indicates its coherency. Models main parameters were found to be the biodegradable fraction *BF* in SW, the maximum value of methane produced by a certain amount of waste C_m, the waste component fraction *Fr* in the first place, followed secondarily by the reaction rate constant k_i. It was also noticed the role of *BF* and C_m in determining the degradable organic carbon *DOC*, a key factor for *LFG* calculation. One contribution was made on the *LFG* combined uncertainty, estimated to be around +/- 50% of the nominal model output, within 68% probability. The use of maximum and minimum values of the key parameters *DOC* and *k* as a way to roughly explore the model uncertainties, instead of a proper combined propagation, showed to be acceptable depending on the DOC model calculation. The assessment carried out in this study allowed to identify the importance of the proper determination of gas generation parameters to estimate landfill gas generation, which is critical for decision-making in LFGE projects.

7. ACKNOWLEDGEMENTS

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