Uncertainty analysis for estimation of landfill methane emissions

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A b s t r a c t : For better estimation of emissions the IPCC Guidelines are followed and the country specific methodology for the waste sector is developed. The database of the Center of Waste Service and Environmental Management in Bratislava has been used as a source of input data. GHG emissions from the solid waste disposal sites are the key source and the actual emission factors are estimated with a high uncertainty level. The Emission uncertainty calculation of landfill by using the more sophisticated Tier 2 - Monte Carlo method is evaluated in this article. For this reasons the software package, which works with probabilistic distribution and their combination, was developed. The results and computational methodology of methane emissions from solid waste disposal sites are presented.

Key words: Monte Carlo method, methane emissions, solid waste and disposal sites

1. Introduction

Global climate change due to the anthropogenic emission of greenhouse gases is the most important environmental problem in the history of mankind. The framework Convention on Climate Change (UN FCCC)[3] – the basic international legal instrument to protect global climate was adopted at the UN conference on the environment and sustainable development (Rio de Janeiro 1992). The Kyoto Protocol (KP), adopted by consensus at the third session of the Conference of the Parties (COP-3) in Kyoto, December

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[3] `http://www.unfccc.int`

1997, enforced the international responsibility for the climate change. The Kyoto Protocol defines the obligation to register and inventory the emission of greenhouse gases (GHG) (CO_2, CH_4, N_2O and F-gases, included HFCs, PFCs and SF_6) according to the adopted IPCC methodology.[4] The growth in concentrations of greenhouse gases in the atmosphere (caused by anthropogenic emission) leads to the strengthening of the greenhouse gas effect and thus to the additional warming of the atmosphere. The present climate models estimate that global average temperature will rise by about 1.4 - 5.8 C by the year 2100.

In the context of the Slovak Republic joining the European Union (1st May 2004), new requirements for legislative implementation arouse in the field of air protection. The European Union considers the area of climate change as one of the four environmental priorities.[5] The Slovak Republic submits the data about GHG emissions in the relevant extend by January, 15th annually, according to the Decision No. 280/2004/EC of the European Parliament and of the Council concerning a Mechanism for Monitoring Community GHG emissions and for implementing the Kyoto Protocol.[6] The purposes for implementing the Decision were the following:

- Monitoring of all the anthropogenic emissions of GHGs in the EU member states,
- Ensuring the progress in fulfilling the reduction targets UNFCCC and the Kyoto Protocol,
- Implementing the Convention and the Kyoto Protocol in the view of the national programs, GHGs inventory, national system and the register of EU and the member states,
- Ensuring completeness, transparency, consistency, accuracy, comparability and the timing in the EC reporting.

[4] Intergovernmental Panel (IPCC - Intergovernmental panel on Climate Change `http://www.ipcc.ch`) was established in 1988 commonly by ECE (UNEP) and World Meteorological Organization (WMO). Its task is to reach the authoritative international consensus in the scientific opinions on climate change. The working groups of IPCC (under the participation of the scientists from the whole world) prepare regular updated information for COP (Conference of the Parties), where the latest knowledge in association with the global warming is included.

[5] New environmental action program: Environment 2010 Our Future, Our Choice

[6] OJ L 49, 19.2.2004, p. 1.

The KP targets for the 'old' EU member states represent the 8% reduction of all the GHGs against a base year for the 2008-2012 period. The different emission or reduction targets were agreed for each 'old' member state with the EU approval as 'burden-sharing agreement' (Article 4, KP).

Several COP/MOP decisions were adopted to implement a methodology for GHGs inventory and national communication under UNFCCC. The following IPCC manuals are actually in use: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventory, Volume 1-3 *(IPCC 1996)*, Good Practice Guidance and Uncertainty Management in National GHGs Inventories 2000 *(IPCC 2000)* and IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry 2003, *(IPCC 2003).* The Slovak Republic, as a member of the European Union and signature country of the UNFCCC is required to provide national inventory and reports on GHG emissions. One of the IPCC sectors identified as a significant source of methane and a key source is the disposal of waste to solid waste disposal sites (SWDSs).

More complex method for estimating methane emissions from solid waste disposal sites (SWDSs) acknowledges the fact that methane is emitted over a long period of time rather than instantaneously. A kinetic approach therefore needs to take into account the various factors, which influence the rate and extent of methane generation and release from SWDSs. The equations presented in IPCC manuals form the base for the first order decay (FOD) method kinetics and are quoted from the Revised 1996 IPCC Guidelines for National Inventories: Reference Manual *(IPCC 1996).* The IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories provide further details on the FOD method, mainly in defining FOD model parameters in terms familiar to users of the default method Tier 1.

This approach can be used to model landfill gas generation rate curves for individual landfill. It can also be used to model gas generation for a set of SWDSs to develop country emissions estimates or can be applied in a more general way to entire regions.

The IPCC methodology and Good Practice Guidelines were used to estimate methane emissions from landfill. The database of the Center of Waste Service and Environmental Management in Bratislava has been used as a source of input data; GHG emissions from the waste sector are the key source, and concerning the actual emission factors (EF), these are estimated with a high uncertainty level.

For a better estimation of emissions we considered to follow the IPCC Guidelines and to develop the country specific methodology for the waste sector. From government engagement it is important to test the preparedness of the Slovak Republic to prepare methane emissions estimation according to the method - Tier 2. There are three main challenges in the application of the Tier 2 method in the Slovak Republic:

- Selection of an appropriate FOD method - Tier 2;
- Preparation of activity data needed as input for the FOD method;
- Reflection of waste management practice changes in the period 1960-2005.

Emissions of methane from landfill were estimated with the methodology First Order Decay (FOD), method Tier 2, according to advises of the expert review team of UNFCCC secretariat and European Commission. All time series were recalculated until 1960 and the complete methodology approach was changed.

These three versions of FOD method were considered for the use as Tier 2 method for estimation of methane emissions from SWDS in the SR. Comparing the situation abroad with the situation in our country, several differences can be identified:

- Most countries are using site-specific data. The methane emissions are calculated for each SWDS (or group of SWDS) separately and then the results are summed to obtain national methane emissions estimations. This approach is not yet possible in the SR, because collected data on municipal solid waste (MSW) do not include the needed characterization of SWDS.
- Historical data on MSW management and disposal are more detailed than data available in the Slovak Republic.
- Data on MSW fractions are collected in more systematic and regular way than is the practice in the Slovak Republic.

As the most appropriate approach the Second version of FOD method was selected, as it is defined in the IPCC Good Practice Guidance. This decision is supported by the following reasons:

- parameters used are better defined and allow direct comparison with the Tier 1 method,
- some of the parameters used are defined as time-variables. This allows modeling of the waste sector transformation in the Slovak Republic in the period 1992-2000.

The structure of the required input data better corresponds with MSW data available for the Slovak Republic (data for the use of multiphase method are not available). The uncertainty of the estimation of CH_4 emissions is mainly caused by uncertainty of statistical data on consumption. Another source of uncertainty is the applied default EFs *(Penman et al., 2000)*. An additional error in calculation of the other greenhouse gas emissions may occur as a result of less exact methods, and it cannot be estimated. The calculation emission uncertainty of landfill by using the more sophisticated Tier 2 - Monte Carlo method is evaluated in this article.

2. Tier 2 or Monte Carlo method

In some cases the pure analytic solution of the investigated problem is difficult to find. For events, where significant inaccuracy of mentioned data is present, the statistical approach is accepted and helps us to include the uncertainty to the final assumption. Knowing the final margin of uncertainty is necessary for the estimation of eventual fluctuation of the analyzed variable. When to the process evaluation the combination of data with different uncertainty is entered to the result, with using a classical statistical approach it can be difficult in some cases to obtain reasonable final information.

One method, which allows us to implement all uncertainty to the final analyses is the Monte Carlo method.

In many applications of the Monte Carlo method, the investigated process is simulated directly. There is no need to describe the behavior of the investigated system, which can be advantageous in some complicated systems. The only important requirement is that this system could be described by probability density functions (PDF) *(Lamoš and Potocký, 1989)*. We will assume that the properties of a system can be described by PDF's.

Once the PDF's are known, the Monte Carlo simulation can proceed by random sampling technique from the PDF's. This approach works with random number generator of random numbers, which have properties of desirable PDF. Many trials are then performed and the expected result is obtained as an average over the number of values. In this case, the statistical structure can be predicted, such as variance, kurtosis and some other higher statistical moments of this simulated result. From these characteristics the estimation of the number of the Monte Carlo trials can be achieved to obtain a result with an expected error *(Suvi and Sanna, 2003)*.

The Monte Carlo method is based on the generation of multiple trials to determine the expected value of a random value. In our case it can be said that this method is uncertainties combination of probability distribution functions for activity data (AD) and EFs. Total emissions are then computed as combination of random numbers for appropriate distribution function for assigned greenhouses gases. The advantage of this method is asymmetry allowance to the statistical distribution (Tier 1 method do not allow asymmetry). This advanced method is useful for data manipulation in the case, when proper input data quality is provided.

3. Landfill methane emissions

For Monte Carlo simulation of CH_4 the second variant of the FOD method was chosen. Details can be seen in *Farkaš (2006)*. There is important information, that from solid waste disposal sites emissions of CH_4 are mainly dependent on the factors from inventory year (amount of waste storage, meteorological conditions, population growth, composition...) and from previous years (managing style of sites...). It is visible that total emissions depend on many factors, which are time dependent. The formulas, which describe these emissions are:

$$\begin{aligned} L_0(x) &= 16/12 MCF(x) DOC(x) DOCF(x) F(x), \\ Fk(t,x) &= (1-e^{-k})e^{-k(t-x)}, \\ MSWL(x) &= MSWT(x) MSWF(x), \\ Q_t(t,x) &= Fk(t,x) MSWL(x) L_0(x), \qquad (1) \\ Q_T(t) &= \sum_x (Qt - R(x))(1 - OX(x)). \qquad (2) \end{aligned}$$

Table 1. Entered parameters to the function for methane emissions production

Q_t	methane generated in the year t (Gg/yr)
t	year of the inventory
x	years for which input data should be added
Fk	normalization factor which corrects the summation
k	Methane generation rate constant (1/yr)
MSWT(x)	Total municipal solid waste (MSW) (Gg/yr)
MSWF(x)	Fraction of MSW disposed in the year x
L_0(x)	methane generation potential (Gg CH_4/Gg waste)
MCF(x)	Methane correction factor in the year x (fraction)
DOC(x)	Degradable organic carbon in the year x (Gg C/Gg waste)
DOCF	Fraction of DOC dissimilated
F	Fraction by volume of the methane in the landfill gas
16/12	Conversion factor from C to CH_4
R(x)	Recovered methane in the inventory year t (Gg/yr)
OX(x)	Oxidation factor (fraction)

The notation is given in Table 1. Formula (1) and terms Q_t represent the contribution of emission from the waste layer imposed in the year 'x' to the year of inventory 't'. The result for inventory year 't' is computed by formula (2), which performs the summation of methane submission from different layers stored in different years.

To estimate the total emission for a chosen year one our presented formulae can be used. The situation starts to be complicated when people begin to assume input data uncertainty. The formulae (1) and (2) show relatively complicated relation among the terms in these functions.

One can suppose that our emissions production is expressed by the function $F(X_i)$, where X_i are factors, which affect the sequential result of emissions (i=1…N, N represents number for factors). Every factor has its own uncertainty, which depends many sources. In some situations it is impossible to express the variation of these sources to the function value. It is possible only to express the interval of eventual values and their statistical behavior. In this case the values X_i can be interpreted as a data set. For example factor X_1 will be represented by random values from an expected range of values. The function value and its uncertainties can be expressed:

$$F(X_i) = F(\bar{X}_i + \delta(X_i)), \tag{3}$$

where $\bar{X}_i$ could represent mean (expected value) or a specially chosen value from a possible range of X_i values. It depends on the solving algorithm. Our question is how the uncertainties of X_i values will affect the function value $F(X_i)$. The interest is to find an expression for $\delta(F(X_i))$.

Suppose that X_i are random variables. For example let X_1 have normal distribution $X_1 \sim N(\mu_1, \sigma_1)$ and $X_2 \sim N(\mu_2, \sigma_2)$. They are independent random variables. In addition it can be expected: $F(X_1 + X_2) \sim N(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2)$. For multiplication the situation is complicated, suppose that $\mu_1 = \mu_2 = 0$. For this situation the result can be written in the form:

$$F(X_1 X_2) \sim \frac{1}{\pi\sigma_1\sigma_2} J_0\left(\frac{|X_1 X_2|}{\sigma_1\sigma_2}\right),$$

where J_0 is a modified Bessel function of the second kind. For exponential distribution, which is a special case of a gamma distribution, one can obtain after multiplication of exponential distribution a Weibull distribution: $X_1 \sim$ Exponential $(\lambda^{-\gamma})$. Then $F(X_1^{1/\gamma}) \sim$ Weibull (γ, λ). From these examples it is visible that direct computation of $\delta(F(X_i))$ is possible only in special cases.

To estimate the properties of $\delta(F(X_i))$, it is possible to analyze the error propagation by linearized theory. Consider the term grouped with the first derivative of Taylor's series for $F(X_i)$. It can be written:

$$|F(X_i) - F(\bar{X}_i)| \leq \sum_i |X_i - \bar{X}_i| \left|\frac{\partial F(\bar{X}_i)}{\partial X_i}\right|,$$

or in equivalent form

$$\delta(F(X_i)) \simeq \sum_i \delta(X_i) \left|F'(\bar{X}_i)\right|. \tag{4}$$

With utilization of the same approach it is possible to take the formula for variance:

$$\mathrm{Var}\left[\delta(F(X_i))\right] \simeq \sum_i \sum_j \left|\frac{\partial F(\bar{X}_i)}{\partial X_i}\right| \left|\frac{\partial F(\bar{X}_j)}{\partial X_j}\right| \mathrm{Cov}\left[\delta(X_i), \delta(X_j)\right]. \tag{5}$$

This simplified approach allows us to avoid the complicated behavior of function $F(X_i)$, and to compute its uncertainty as a linear combination of its variables uncertainty, see formula (4). For the variance, there is no linear relation, but when the correlation among factors X_i is suppressed, and $X_i \sim N(\mu_i, \sigma_i)$, then for $\delta(F(X_i))$ a noncentral chi-square distribution can be assumed.

This simple approach has a limitation of applicability. It shows error spreading and it forms a scheme of uncertainty interactions. Formula (4) can be prescribed in the applicable form:

$$\delta(F(X_i)) \simeq \sum_i \frac{\delta(X_i)}{\bar{X}_i} \left|\bar{X}_i F'(\bar{X}_i)\right| ,$$

or with introducing the new functions:

$$\delta(F(X_i)) \simeq \sum_i \frac{\delta(X_i)}{\bar{X}_i} \left|G(\bar{X}_i)\right| , \tag{6}$$

where $G(\bar{X}_i) = \bar{X}_i F'(\bar{X}_i)$. This expression shows the linearized form of the uncertainty combination. When $\delta(X_i)$ is substituted with a value, which represents the 95% confidence interval, then the ratio $\delta(X_i)/\bar{X}_i$ represents the percentual contribution to the total uncertainty. The result is a linear combination of these percentual submissions. It is obvious that the linearized approach can be effectively used only in the case when $|G(\bar{X}_i)| \ll 1$. On the other hand it shows us that PDF's of $\delta(X_i)$ can play an important role within the process of uncertainty combination. From this knowledge it is clear that one cannot take simply errors from $\delta(X_i)$ and sum them together without investigating the probability distribution function of $\delta(X_i)$. The application of our initialization records with applied values to our FOD model confirms apprehension from linear theory limitations. The uncertainty result for total emissions exceeds about two times the mean value. This result, as we will see after the application of a more sophistical method, does not represent the reality.

The method Monte Carlo can be conveniently used for uncertainty problem solving. One requirement is to know the distribution function of uncertainties. This approach allows us, with using a power of computer machine, to simulate the complete properties of the final probability distribution function, $\delta(F(X_i))$ and to obtain the required statistical characteristics. In this point one should be attentive, how uncertainties are specified. In the case when measurement of data is available the situation is well solvable. In the case of data absence the special estimation is provided. There are special recommendations in the literature *(IPCC Guidelines, 1996)*, how to arrive at adequate results.

Table 2. Probability distribution functions and their basic characteristics, mean value and the 95% confidence interval expressed with two values min. and max. The units of parameters are defined in Table 1

Category	Mean value	min/max	Distr. fun.
K	0.065	0.0357:0.2145	triangular
FO	0.500	0.4000:0.6000	triangular
FN	0.500	0.0000:0.6000	triangular
MSVL	0.000	-1.9590:1.9590	normal
DOCF	0.600	0.4200:0.7680	triangular
DOCX	0.120	0.0600:0.1440	triangular
MCFN	1.000	0.7000:1.0000	triangular
MCFO	0.600	0.3000:0.9600	triangular
OX	0.050	0.0025:0.9750	normal

For this reasons the software package, which works with probabilistic distributions and their combination, was developed. With the help of AuvTool software, useful tools for uncertainties estimation are provided. In the developed packages the next statistical distributions are supported: Gumbel, Exponential, Weibull, Lognormal, Uniform, Triangular, Beta, Binomial, Negative binomial, Chi-squre, Noncentral chi-square, F, Noncentral F, Gamma, T, Noncentral T, Normal and Poisson.

For the specification of the probability distribution of AD and EF there is a variety of inputs. For two parameters distributions the mean value and values representing 95% confidence interval are directly expressed. For three parameters distribution there is place for tuning the 95% confidence interval.

To solve equations (1) and (2) with the Monte Carlo method it is necessary to specify the uncertainty of parameters, which enter our formulas. The profiles of PDF's function are obtained after expert consultation and IPCC Guidelines suggestions. The result of setting PDF's efforts is summarized in Table 2. In Table 2 some parameter values should be explained. Parameter 'F', present in the equations (1) and (2), is split to the variable 'FO' and 'FN'. The variable 'FO' represents bigger uncertainty, which was observed until year 1994, and 'FN' uncertainty, which was observed after year 1994. Parameters 'MCFN' and 'MCFO' are defined analogically. The difference from previous case is that the mean value is changed, too. For this reason 'MCFO' is valid until 1993, while between the years 1994 and 2001 the mean value is linearly interpolated between the values 'MCFN' and

'MCFO'. After year 2001 the value 'MCFN' is valid. Special explanation is required regarding parameter 'MSVL', which is a product of multiplication of 'MSWT' and 'MSWF'. From Table (2) it seems that 'MSVL' produced negative contribution to the final emissions. This is not true. In this table we exploit the possibility to easily transform the standard normal distribution to the normal distribution. Parameter 'MSVL' varies during the analyzed period 1960-2005 significantly, the mean value and 95% confidence interval varies during this period, but the PDF has a feature of the normal distribution. The uncertainty of 'MSVL' until 1995 was taken to 50% of the mean value. After 1995 the uncertainty of 'MSVL' was taken to 10% of the mean value. The variation of the mean value of the 'MSWL' can be seen in Fig. 1. 'DOCX' value linearly changes from value 0.06 in 1960 to value 0.12 in 1990. After year 1990 this parameter has a constant value. For the parameter 'OX', the values from table are valid only in the period 1994 to 2005. Beyond this time the zero value is assumed.

The specification of the parameters value is not a main topic of this article. Presented values are for illustration, more details about FOD model can be obtained in *Farkaš (2006).* The main goal of this contribution is also to specify the distribution function that belongs to the parameters.

After the application of the Monte Carlo method to the FOD model the final probability distributions are obtained for every spotted year. This approach allows us to see detailed variation and combination of input parameters and their distribution functions. As was shown, the interaction of PDF's is not simple. Final distribution function for total methane emission for chosen year 2005 can be seen in Fig. 2. This result is for 20000 trials. A number of trials has influence on the result precision. Complete statistical characteristics such as mean value, median, standard deviation and 95% confidence interval are presented in Fig. 3. For the last seven years Table 3 is added to better specify the results.

To see the influence of PDF's change on the total emissions, we try to modify the PDF's profiles for every input parameter, defined in Table 2. Every profile was changed to the normal distribution, mean values were retained. Uncertainties were changed, symmetrical uncertainties were set for parameters. The uncertainty is presented in Table 4.

Results for sensitivity of input parameters are simply verified. The result for PDF's exchange can be seen in Table 5. The mean value and average

Table 3. Statistical characteristics for last seven computed years, mean value (Gg/yr), average(Gg/yr), standard deviation (Gg/yr) and 95% confidence interval is expressed with two values 2.50% and 97.50%. Relative percentual values related to the mean value are presented too. On the next absolute minimum and absolute maximum is shown

CH_4/Yr	1999	2000	2001	2002	2003	2004	2005
mean	39.511	39.339	39.162	44.608	47.099	44.899	42.979
average	40.056	39.884	39.710	45.219	47.739	45.503	43.558
st. dev.	9.360	9.378	9.324	10.603	11.181	10.646	10.182
2.50%	23.381	23.225	23.162	26.404	27.893	26.599	25.454
Percent	-41.629	-41.769	-41.672	-41.608	-41.571	-41.545	-41.563
97.50%	59.782	59.490	59.210	67.350	71.069	67.730	64.806
Percent	49.247	49.156	49.105	48.943	48.868	48.846	48.780
Abs.Min	14.826	15.306	15.250	17.377	18.357	17.506	16.765
AbsMax	77.227	77.048	76.668	87.385	92.336	88.079	84.375

Table 4. Statistical characteristics of uncertainty for input parameters for year 2005

Param.	K	FO	FN	MSVL	DOCF
Interval	-100%:100%	-20%:20%	-20%:20%	-97.5%:97.5%	-30%:30%
Param.	DOCX	MCFN	MCFO	OX	
Interval	-50%:50%	-30%:30%	-50%:50%	-95%:95%	

Table 5. Statistical characteristics for year 2005, mean value (Gg/yr), average (Gg/yr), standard deviation (Gg/yr) and 95% confidence interval is expressed with two relative percentual values 2.50% and 97.50%. On the next absolute minimum and absolute maximum is shown

mean	average	st. dev.	2.50%	97.50%	Abs.Min	AbsMax
44.796	46.476	19.177	-71.042	92.978	0.131	171.514

did not change significantly. Other statistic characteristics changed approximately by a factor of two. This result shows a strong dependence on the sort of PDF's and it calls for tidy approach in PDF's selection.

4. Conclusion

The main topic of this article was to eliminate the uncertainty of methane emissions produced by solid waste disposal sites. From our analyses seems that uncertainty of emissions are strongly dependent on the PDF's setting.

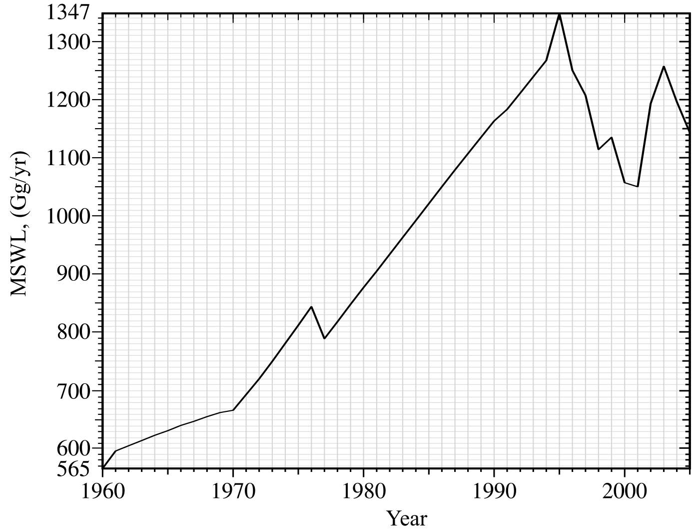

Fig. 1. Municipal solid waste (MSWL) mean value variation during the period 1960-2005.

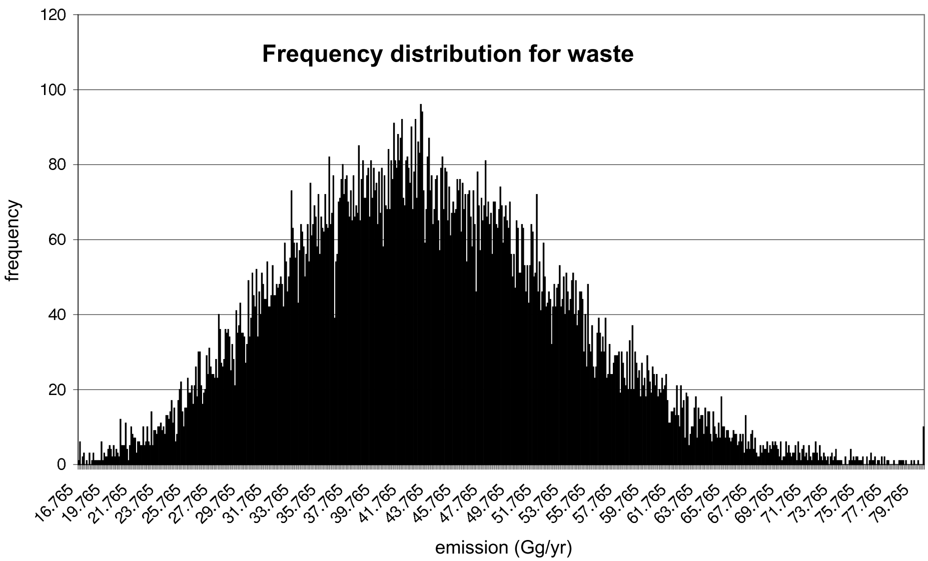

Fig. 2. Total emission of CH_4 for the year 2005.

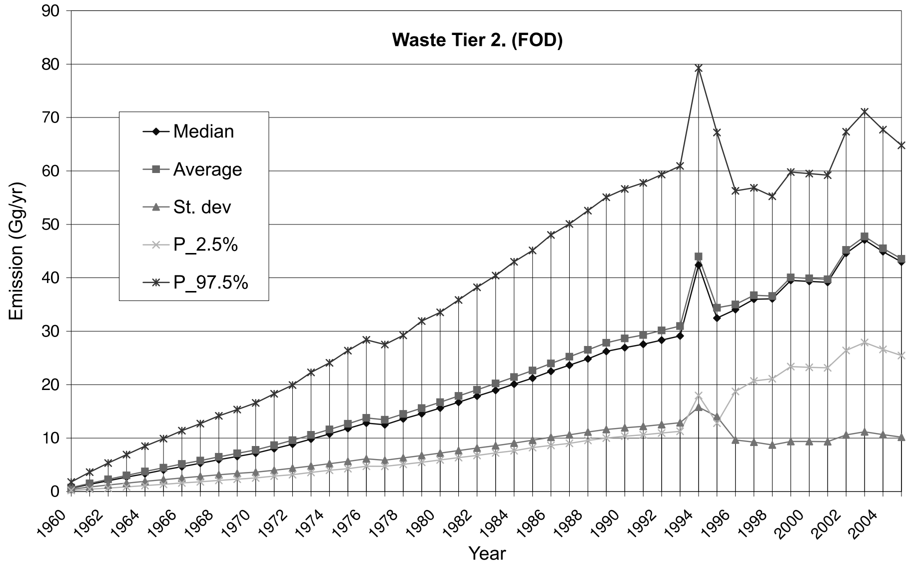

Fig. 3. Variation of median, average, standard deviation and 95% confidence interval expressed by min. and max. values during the period 1960-2005.

These features were identified by simplest linear analyses of uncertainty of total emissions and in the second case with changing PDF's setting. The essential result from our study is the fact that total uncertainty was reduced comparable to IPCC default recommended value. This value is 50% for total methane emissions from SWDS. This default uncertainty is applicable to the Tier 1 default method. From this value in the Tier 1, the key sources are identified by categories magnitude which adds up to over 95% of the total emissions or emission trend. In Tier 2 the 90% of the level or trend uncertainties are also taken for the key sources specification *(Penman et al., 2000)*. Specification and identification of the key sources are important for economy and government institutions to obtain an overview of emissions unload. During the uncertainty computation the emitting of CH_4 from underlayer and many other factor as meteorological conditions, managing of sites are included. These dependences are expressed in the FOD model, which was solved by Monte Carlo simulation. Spreading of emission uncertainty during the analyzed period was obtained. From the computed result an increase of precision of emissions is observed. In spite of high inaccuracy on the input data in the beginning of the examined period (this uncertainty has influence on the current uncertainty) relatively valuable results are obtained.

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