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INTEGRATED ECONOMIC MODEL OF WASTE MANAGEMENT: CASE STUDY FOR SOUTH MORAVIA REGION

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Abstract

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The paper introduces and discusses the developed integrated economic model of municipal waste management of the Czech Republic, which was developed by authors as a balanced network model for a set of sources (mostly municipalities) of municipal solid waste connected with a set of chosen waste treatment facilities processing their waste. Model is implemented as a combination of several economic submodels including environmental and economic point of view. It enables to formulate the optimisation problem in a concise way and the resulting model is easily scalable. Model involves submodels of waste prevention, collection and transport optimization, submodels of waste energy utilization (incineration and biogas plants) and material recycling (composting) and submodel of landfilling. Its size (number of sources and facilities) depends only upon available data. Its application is used in the case study of the South Moravia region with verification of using time series waste data. The results enable to improve decision making in waste management sector.

economic model, waste management, municipal waste, optimization

The paper discusses a model of integrated municipal waste management (Hřebíček, Hejč, Soukopová, 2010; Soukopová, Hřebíček, 2011; Soukopová, Kalina, 2012) and introduces new model of production of municipal waste to assist in identifying alternative municipal waste management strategies and plans that meet cost, material, energy, and environmental emissions objectives of European Union (EU).

Waste is an unavoidable by-product of human activities. Economic development, urbanisation and improved living standards in municipalities increase the quantity and complexity of generated *municipal solid waste* (MSW). The decisions in the area of MSW management are not only very capital-intensive, but also difficult from environmental and social points of view. There is the need to develop, master and implement simple but reliable *integrated municipal waste models* (IMWM) and information and communication technology (ICT) tools that will help decision-makers to analyse waste management processes (Hejč, Horsák, Hřebíček, 2008; Hřebíček, Hejč, Soukopová, 2010; Soukopová, Hřebíček, 2011).

The MSW is all waste generated within the municipalities (cities and villages) by the activities of its inhabitants (households) and businesses (e.g. trade waste), which is separated into its components and transported to waste treatment facilities, where is recovered or disposed. The MSW normally contains the remains of food and vegetables, paper, plastic, glass and metal containers, printed matter (newspapers, magazines, and books), destroyed products, ashes and rubbish, used or unwanted consumer goods, including shoes and clothing. The MSW (or its separated components) can be composted, used as raw material (paper, plastic, glass, and metals), used in bio-gas, energy recovery (incineration) plants or land-filled (Hřebíček *et al.*, 2009). The separation of its components may take place at the source (separate collection in the municipalities) or in the facilities.

The main objective of the paper is introducing the new more accurate model of production of municipal waste in the Czech Republic, which builds on the previously developed model Hejč and Hřebíček (2008) and its modifications. The larger files of open government data of the Ministry for Regional Development (MRD) and the Ministry of Finance (MF) are used in the new model instead of past one. We show that the new model has a more explanatory power and its parameters are not collinear. At the same time is able to take account of the more publicly accessible data.

METHODS AND RESOURCES

We introduce production and prediction submodel of municipal waste management which improves the models of (Hřebíček, Hejč, 2008; Hřebíček, Hejč, Soukopová, 2010; Soukopová, Hřebíček, 2011; Soukopová, Kalina, 2012).

The production and prediction submodel development

The fundamental part of the integrated economic model of waste management (Soukopová, Hřebíček, 2011) is a production and prediction submodel which serves as a tool for the estimation of annual waste production in different waste streams and municipal territorial units. Hřebíček and Hejč (2008), Hřebíček, Hejč and Soukopová (2010), Soukopová and Hřebíček (2011) developed the submodel of waste production for municipality:

$$P = inh \times spec \times std \times sz \times unemp \times hsg \times heat, \quad (1)$$

where

P............ the amount of the MSW production of given municipality per year (in tons),
inh......... total population of municipality,
spec........ the specific waste production coefficient (estimated by reference values of other coefficients),
std.......... the standard of living coefficient,
sz........... the size of the community coefficient,
unemp ... the unemployment rate coefficient,
hsg......... the type of housing (recreation, blocks of flats, empty houses…) coefficient and
heat........ the type of heating coefficient.

This model was used by the Ministry of Environment for the modelling of the regulation of waste management of the Czech Republic and a decision support of the allocation of subsidies from EU (Hřebíček, Hejč, Soukopová, 2010; Soukopová, Hřebíček, 2011) and for evaluation of cost and price relationships for the municipal waste management of the Czech Republic. This submodel was presented and discussed on the European Environment Information and Observation Network (Eionet) workshop in the last year together with models of European Environment Agency (EEA) and General Directorate of Environment (DG ENV) of European Commission (EC). Following recommendation of this workshop we decided to develop more precise model of MWM production. The aim of new developed submodel is to deduce the most probable level of waste production, which may not be explicitly known, and its future trend from other parameters, ostensibly unrelated to a waste management. The smallest territory unit used for waste production estimation is a municipality (i.e. village, town or city), but this new submodel could be simply adapted for computations over larger areas (district, county, region). Moreover, when working with smaller units, modeller can join them into groups and gain aggregated outcomes for larger areas by modelling their individual parts. The size of one municipality could appear to be too small for any conceptual waste management strategy planning, but its eligibility clearly results from the fact, that each municipality in the Czech Republic is responsible for the (municipal) waste management.

A key task for the estimation and prediction of the waste production is sufficient amount of information about the territory units. Unfortunately, the waste production data themselves are not available from public information sources except of several aggregated statistics (http://isoh.cenia.cz/groupisoh/). However, there are very extensive public sources of information about municipalities in the Czech Republic. For example, the MRD offers plenty of publicly accessible infrastructure and social statistics via the web portal of *Regional Information Services* (http://www.risy.cz) and also the MF provides the *Financial System and State Accounting Information* (http://wwwinfo.mfcr.cz/ufis/) with information about municipal expenses on waste management in HTML and XML form.

After an analysis we choose data from the *Regional Information Services* (RISY) for a *multivariate linear regression* (MLR) method which serves as an estimation tool for revealing of hidden dependencies between publicly accessible parameters of municipalities and their waste production.

For a training phase of MLR (e.g. calibration of the model) it is necessary to have a subset of municipalities with known level of the waste production. This set also serves as test subset (i.e. allows the estimation of average difference between the real and the estimated production). In this case study, the municipalities from South Moravian Region of the Czech Republic (ISO 3166-2 CZ-JM) was chosen as representative sample.

Municipal parameters wrapper

The first step for the development and a reliable model is its filling with appropriate data. This is ensured by an automatic wrapper, which uses the exactly given structure of the RISY. We chose 14 parameters of municipalities following experiences with parameters of the previous models developed in (Hřebíček, Hejč and Soukopová, 2009; Hřebíček, Kalina and Soukopová, 2011; Soukopová and Hřebíček 2011). They are potentially relevant parameters for the waste production estimation of the any municipality: p_1*-total population of the municipality;* p_2*-portion of the inhabitants older than 60 years;* p_3*-unemployment;* p_4*-gasification of the municipality;* p_5*-acreage of the municipality cadastre;* p_6*-acreage of lawns;* p_7*-acreage of gardens;* p_8*-number and type of schools;* p_9*-number of healthcare facilities;* p_{10}*-number of economic subjects;* p_{11}*-latitude;* p_{12}*-longtitude;* p_{13}*-altitude;* p_{14}*-status* (village, small town (městys), town, district – county – regional town, capital).

Computational profiles of the model

After the creation of a table containing all the municipalities in the area of interest, nonnumeric parameters (p_4-gasification, p_8-number and type of schools, p_{14}-status) are rated by values, which provided the best results in the period of pilot testing of the model. Moreover, there is a possibility of some modification in the model structure, to define a specific user profile containing set of all 14 additive constants a_i, which are imputed to each parameter p_i. This possibility serves to maximization of the variance of each parameter p_i, which improves the ability of the parameter p_i to explain the dependence of the waste production on it. E.g. the latitude varies between 48° and 60° of the northern, thus the maximal variance is reached by deducting of 54° and the additive constant is therefore –54°.

The next step consists of a formulation of the expected form of the dependence of the waste production on the parameters p_i of the municipalities. Because there is not quite clear form of this dependence, the model allows its users to create in the frame of user profile their own equation of an arbitrary form varying from linear dependence on single parameter p_i up to complicated sum of various parameters product. In general, there is possible to define from 1 to 20 summands, each by an arbitrary combination of 1 up to 14 parameters. The sum of these summands S_j multiplied by variables representing searched coefficients is then interlaced between points of a known waste production for a sample of municipalities from the region and the best fitting solution provides the values of searched coefficients a_i.

In general, the form of each summand S_j is given by the equation:

$$S_j = \prod_{i=1}^{n} (p_i + a_i), \tag{2}$$

where

S_j.......................... denotes j-th summand of the production equation,

p_i.......................... denotes the i-th parameter of the municipality,

a_i.......................... represents the i-th additive constant entered by the expert user (a default set is available in the model) and

$n \in \{1, \ldots, 14\}$.... represents the number of parameters p_i chosen for the definition of the j-th summand by the user.

The general form of the waste production equation P is then given as:

$$P = \sum_{j=1}^{m} (c_j \times S_j) + e, \tag{3}$$

where

P.......................... denotes the overall waste production,

S_j.......................... denotes the j-th summand,

c_j.......................... denotes the j-th coefficient (searched by Multiple Linear Regression - MLR),

e.......................... denotes an error of the estimation and

$m \in \{1, \ldots, 20\}$... represents the number of summands defined by the user.

Concisely said, the more different summands in the equation (3), the smaller error of the estimation e.

Assessment of MLR coefficients

The method of least square errors (Budíková, Králová, Maroš, 2010) is used in computational part of the model. First, the square error is expressed for each municipality from the equation (3) and then summed for all municipalities in the group with known production, which serves as a calibration sample:

$$E = \sum_{\alpha=1}^{\omega} e_\alpha^2 = \sum_{\alpha=1}^{\omega} (P_\alpha - \sum_{j=1}^{m} (c_j \times S_{j\alpha})^2, \tag{3}$$

where

ω.... denotes the number of municipalities with the known waste production (calibration sample of municipalities) and the other notation is the same as above, but for the α-th municipality with the subscript α.

The minimization is conducted as finding a solution of a set of linear equations generated as partial derivatives of equation (4) gradually by all the coefficients :

$$\begin{gathered}
\sum_{\alpha=1}^{\omega} -2 \times S_{1\alpha} (P_\alpha - \sum_{j=1}^{m} (c_j \times S_{j\alpha})) = 0 \\
\sum_{\alpha=1}^{\omega} -2 \times S_{2\alpha} (P_\alpha - \sum_{j=1}^{m} (c_j \times S_{j\alpha})) = 0 \\
(\ldots) \\
\sum_{\alpha=1}^{\omega} -2 \times S_{m\alpha} (P_\alpha - \sum_{j=1}^{m} (c_j \times S_{j\alpha})) = 0 .
\end{gathered} \tag{5}$$

This approach is correct for finding the solution with minimal sum of square errors E, which is useful when working with larger territorial units. In the case of searching waste production estimations for individual municipalities, it is more suitable to minimize relative square errors sum, derived as a sum of square errors divided by the population of each municipality:

$$e_{rel,\alpha} = \frac{e_\alpha}{inh_\alpha} = \frac{P_\alpha - \sum_{j=1}^{m}(c_j \times S_{j\alpha})}{inh_\alpha}, \tag{6}$$

where

e_α ....denotes the error of α-th municipality,

$e_{rel,\alpha}$...... denotes the relative error of α-th municipality and

inh_α......denotes the population of α-th municipality.

This adapted approach ensures, that the average relative error of estimation will be the same for all the municipalities in the model, which is necessary when assume, that absolute error of hundreds of tons is negligible in the case of city, but far exceeds a production of any small village.

When the solution is found, all the coefficients in the equation (3) are known and the user could simply gain the production of any municipality with known parameters p_i, i.e. at least for all the municipalities in the Czech Republic.

Prediction module

If the form of the dependence (production equation (3)) and coefficients are known, it is simple to model the change of production induced by a change of initial parameters. The integrated economic model of waste management (Soukopová, Hřebíček, 2011; Soukopová, Kalina, 2012) allows the user to specify several trends – annual percentage change of total population in municipalities of different statutes (i.e. capture the urbanization of the population), the change of the potion of inhabitants over 60 years also in municipalities of different statutes, expected GDP and unemployment development. This percentage change is then embedded in natural exponential form into production equation, by which the user can compute an estimation of future waste production development.

Economic models for facilities

We developed cost economic models for all types of facilities F_j (j = 1, …, M), including mechanical biological treatment (MBT) plants, incineration plants with energy recovery (ERP) and landfills (Hřebíček, Hejč, Soukopová, 2010), composting and biogas plants (Hřebíček, Kalina, Soukopová, 2011). These models are similar and therefore the complex economic model for a generic facility F was presented by Soukopová and Hřebíček (2011). A price p_t of one ton of the waste treatment was calculated for a new composting, biogas, MBT and ERP plant F depending on the amount of available waste in the surroundings of considered facility as output of production submodel. This calculation is based on the financial and economic analysis and financing methods for the measuring the efficiency of investment, see Valach (2006), Soukopová *at al.* (2011) etc. We used the *Net Present Value* (NPV) as the basic calculation method for the price p_t. By comparison of the price p_t and prices for landfilling one ton of waste p_l (including waste taxes), the fact could be immediately find out, whether the considered facility is able to succeed in the waste market or not.

RESULTS AND DISCUSSION

We implemented above model, where we used municipal waste management data from the South Morava region collected in the framework of the implementation of the legal obligations of the reporting agents of waste producers and waste treatment facilities of the Czech Republic. The source of information to our model was data from the annual reports of municipalities. Data from these annual reports are sent electronically to CENIA, the Czech environmental information agency via the Information System of Implementation of Reporting Obligations (https://www.ispop.cz/magnoliaPublic/cenia-project/uvod.html) every year. They are verified by county authorities and finally by CENIA.

Chosen 14 free available parameters of individual municipalities of the South Moravia provided, using the best set of additive constants and non-numeric parameters rating, an average total deviance of *mixed municipal waste* (MMW) production in the municipalities about 25.1% opposite to reported values. This result, with a respect to relatively high coefficient of variation c_v = 7.45, responses to the high coefficient of determination $R^2 > 0.999$. The results in Tab. I are significantly better in the case of aggregation MMW municipalities on counties. The average total deviance decreases to 10.3 % as could be seen from the Tab. I.

General structure of the model allows to define almost unlimited number of predictors (the settings of additive constants and the selection of the parameters for each predictor), which of course raises the question of a meaningfulness of the selected model design. In fact, there is no function which could for any user-selected combination check statistical significance and interdependence of predictors (correlations, (multi)collinearity) or normality of residuals in the model; thus, if necessary, it is needed to analyze compliance with the Gauss-Markov requirements separately. For the mentioned case study of the South Moravia region were defined 19 individual predictors. Subsequent analysis of mutual correlations showed that six of these predictors were strongly ($\rho > 0.8$) and statistically significant correlated with other predictors. After exclusion of these predictors, the new model based on 13 remaining predictors was tested on normality of residuals using the Kolmogorov-Smirnov test. The coefficient of determination remained almost unchanged ($R^2 > 0.999$). The results showed not only those

I: *Comparison of production MMW in counties*

County (ORP)	County town	Reported production	Model production	Deviance
		t/year	t/year	%
6201	Blansko	9,999	11,483	14.85
6202	Boskovice	10,905	11,057	1.39
6203	Brno	72,037	72,005	–0.04
6205	Bučovice	3,566	3,645	2.21
6206	Hodonín	14,335	14,014	–2.24
6207	Břeclav	7,409	8,089	9.18
6208	Ivančice	5,130	5,412	5.50
6209	Kuřim	5,003	4,692	–6.21
6210	Kyjov	13,825	12,877	–6.86
6211	Mikulov	3,667	4,618	25.93
6212	Moravský Krumlov	5,225	5,050	–3.35
6213	Pohořelice	2,982	3,098	3.88
6214	Rosice	3,527	5,284	49.85
6215	Slavkov u Brna	3,785	4,602	21.59
6216	Šlapanice	13,106	13,145	0.30
6217	Tišnov	6,009	6,273	4.40
6218	Veselí nad Moravou	9,608	9,031	–6.00
6219	Vyškov	10,695	11,455	7.11
6220	Znojmo	15,742	20,407	29.63
6221	Židlochovice	5,953	6,246	4.93

residues do not have a normal distribution, but also that to achieve it is very difficult with the given set of parameters. Further analysis indicated a strong mutual dependence especially of the parameters population (p_1) and number of economic subjects (bus) ($\rho = 0.983$, $p < 0.001$) but also showed that the deviation of the residues distribution from the normal distribution is caused only by a few deviant municipalities, with substantially (in orders) different values of MMW production. After exclusion 4% of most extreme communities (there is a suspicion of a reporting error in orders, e.g. the amount of MMW was reported in kg instead of tons), the result of Kolmogorov-Smirnov test has been satisfactory ($p = 0.061$) and therefore could be confirmed the normality of the residuals distribution (also well observable form Q-Q plot). Also the relatively high variance inflation factor (of the order up to hundreds) shows that the correlation of predictors should be considered, however, given the relatively high number of records and the great value of coefficient of determination, it could be concluded, that the regression works well.

This result could be considered as relatively good (Chen, Chang, 2000) as well in comparison with non-linear methods (Noori, Kabassi, Sabahi, 2010). The total number of municipalities in training subset was 517, which represent 8.3% of all municipalities in the Czech Republic. The strongest correlation with the waste production was found for the total population of the municipality, the portion of older inhabitants and unemployment.

The consequent economic submodel deploying NPV approach is strictly dependent on inserted values of key financial parameters such as the inflation and rate of the interest, number of loans necessary for the facility construction, prices in waste management (Soukopová, Hřebíček, 2011) etc. The most obvious result is the fact, that present fees for waste disposal are too low for enabling the cost-effective construction of great waste facilities such as incineration plants or MBT. However, the key role in an investment assessment plays a size of a subsidy support, which could significantly compress the initial construction costs and thus make advanced waste treatment methods able in the competition with disposal on landfills.

Taking into account macroeconomic conditions at the beginning of 2013, the price for treatment of one tone of mixed municipal waste varies from 1,361 CZK in the case of the biggest considered incinerator in Karviná (of capacity 200 kt/year) with the payback period of 20 years and subsidy representing 20% of the investment costs up to 1,679 CZK for smaller mechanical-biological treatment plant (MBT) in the Eastern Bohemia region with the capacity of 50 kt/year, the same payback period of 20 years and the subsidy of 40%.

Together with modelling, a landfill fee survey was conducted on 58 different landfills, which represent 39.7% of all landfills relevant for mixed municipal waste in the Czech Republic (Soukopová *et al.*, 2011; Soukopová, Struk, 2012). The average value of landfill fee was 1.339 CZK/t, which attacks the lower limit of modelled treatment fees, thus only a little increase of landfill fees is needed in order to a diversion of the mixed municipal waste from landfills to advanced treatment facilities, of course while maintaining the expected level of subsidy support.

SUMMARY

The developed model enables to estimate the present and future waste production for territorial units of different scale, based on multivariate linear regression and from the information on the known level of production to decide on a waste treatment facility construction. We used 14 free available parameters of individual municipalities and by several method of testing achieved an average total deviance 25.1% for mixed municipal waste production in comparison with really reported values.

By a classic NPV approach the price for one tone of the treated waste is consequently computed for each facility considered in the model and by comparison with present waste disposal prices and transport costs, a decision on cost-effectiveness of the facility is made.

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