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International Environmental Modelling and Software Society (iEMSs)
2010 International Congress on Environmental Modelling and Software
Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada
David A. Swayne, Wanhong Yang, A. A. Voinov, A. Rizzoli, T. Filatova (Eds.)
http://www.iemss.org/iemss2010/index.php?n=Main.Proceedings

Integrated Model of Municipal Waste Management of the Czech Republic

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Abstract: An integrated model of municipal waste management of the Czech Republic was developed as a balanced network model for a set of municipal solid waste (MSW) sources (mostly municipalities) connected with a set of chosen waste treatment facilities processing their waste. The model involves composting, energy utilisation, material recycling, and land-filling. It is implemented as a combination of four sub-models (GIS transport sub-model, quantification and composition of MSW sub-models, cost economic sub-models of all facilities and sub-model optimizing greenhouse gases expressed as CO_2 equivalent) and it is easily scalable. It enables the optimisation of environmental impacts (land-filling and greenhouse emissions). Its application is demonstrated in the case study as a decision support tool for the planning allocation of potential facilities of waste recovery instead of land-filling.

***Keywords**:* integrated waste management model; municipal solid waste; waste cost modelling.

1. INTRODUCTION

Waste is an unavoidable by-product of human activities. Economic development, urbanisation and improved living standards in cities 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 tools that will help decision-makers to analyse waste management processes. This paper discusses an integrated model of municipal solid waste management to assist in identifying alternative MSW management strategies and plans that meet cost, material, energy, and environmental emissions objectives of European Union (EU).

The MSW is considered like all waste generated within the community (as well as the source MSW) by the activities of inhabitants (households) and businesses (e.g. trade waste), which is separated into its components and transported to waste treatment facilities. 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. Chosen components of MSW are collected separately, and thus, they are balanced separately. The waste (or its components) can be composted, used as raw material (paper, plastic, glass, and metals), used in bio-gas, energy recovery (incineration) plants or land-filled. The separation of its components may take place at the source (separate collection in the municipalities) or in the facilities. So we define the individual waste streams, which are mass balancing.

Earlier this decade, the development of models of waste management began moving towards the *integrated model waste management* (IMWM), which is designed to minimise the economic costs and / or environmental impacts, see Berger et al. [1999], Wang [2001], Haigh, Shmelev nad Powell, Yeomans [2006].

Consider the IMWM discussed by Hřebíček et al. [2009], [2010] which consists of the set of MSW sources (municipalities) of the Czech Republic connected by the road network with the set of waste treatment facilities (composting, bio-gas, mechanical-biological treatment (MBT) and pre-treatment of recyclable waste plants, incinerating plants with energy recovery (ERP) and landfills), where MSW (or its components separated at source) is transported to chosen facilities for recovery or final disposal. The material balance is examined in terms of material flows between MSW sources and waste treatment facilities. The production of MSW in the Czech Republic is approximately 3,2 million tons of MSW annually (in 2008), and most (85 percent) is land-filled.

In developing an IMWM for the Czech Republic, we started from the models available in literature. Since the early 1990s, a number of IMWMs have been developed, which were based on life cycle analysis (LCA), i.e. materials and energy balances, see McDougall et al. and Solano et al. [2002]. Most available models are static, respectively deterministic and quantify the uncertainty of estimates due to random nature of input values. Another disadvantage of models based only on the LCA is that they do not allow optimising the allocation of waste treatment facilities from sources and / or quantifying the transport emissions. We tried to reduce the greatest uncertainty of our model by the estimation of the composition of municipal waste, waste separation, varying the proportion of resources, varying quantities of trade waste and the like.

The developed IMWM for the Czech Republic consists of the combination of four sub-models, where we used following tools:

a) The geographic information system (GIS) *ArcMap,* which computed a transport matrix linking the sources MSW and waste treatment facilities and the simple model, which generated emissions from the transport of MSW and enable to find the closest facility.
b) The sophisticated model of Hejč et al. [2008] for the determination of the quantity and composition of MSW at every source (municipality) or the database of collected data from annual waste reports of municipalities regarding the quantity and separated components of MSW.
c) The cost economic sub-models of every type of waste treatment facility including the generation of the emissions of MSW treatment.
d) The software *LINGO* for the carbon emissions optimisation of allocated waste treatment facilities with the choice of either the economic or the environmental point of view.

The above IMWM requires criteria (prioritisation) from decision-makers (government regulators), which may involve an acceptable level of pollutant emissions and costs, as well as a reduction of landscape and biodiversity or prevent a pollution of groundwater and surface water. Practically, such optimisation comes into consideration for regulators when deciding on localisation of a new facility (technology and capacity) and / or closure of existing facilities, the regulation of their capacities and the like. Some chosen feasible minimum is usually acceptable for regulator without optimisation.

2. TRANSPORT NETWORK MODEL

Consider the MSW flows at the Czech Republic among all sources (municipalities) S_i, (i=1…N), N = 6 245 and all waste treatment facilities F_j, (j=1…M), M = 307, where ML = 237 is the number of landfills. Consider these MSW flows in a continuous manner and mass balance between sources and facilities carry out over a longer period of time (annual reporting). We built the transport matrix $\boldsymbol{D} = \{d_{ij}\}$, ($NxM$), of real transport distances d_{ij} (e.g. road maps) among all sources S_i and all facilities F_j and the vector of the distance $\boldsymbol{dc} = \{dc_i\}$ (Nx1) of the source S_i from its closest landfill F_c, $c \in \{1, \ldots, M\}$.

We have used the GIS program *ArcMap* 9.2 with its extension *Network Analyst* 9.2 from ESRI for the analysis of the closest facility (e.g. landfills) to the individual sources (municipalities).

Figure 1. Map of landfills of the Czech Republic.

The *Network Analyst* program enables us to implement networking analysis - finding the shortest path between two points, finding time to travel between two points, etc. Users can create and maintain network data sets in shape file, personal geo-database, and enterprise geo-database formats. By using *ArcGIS Network Analyst*, we created simple applications that provide us transport distances among all *M* sources and *N* facilities, find closest facilities, and create the distance matrix ***D*** and the vector ***dc***.
We used municipalities and roads layers of the Czech Republic for ArcGIS Network Analyst from the open-source project *FreeGeodataCZ data package*. It incorporates an advanced connectivity transport model that can represent complex scenarios, such as multi-modal transportation networks.

3. MODEL OF QUANTITY AND COMPOSITION OF MSW

The developed model of quantity and composition of MSW is based on the production of MSW in each municipality of the Czech Republic and was published by Hejč and Hřebíček, Hejč et al. [2008]. They described formally the simple model of MSW production as the function of appropriate variables taking into account specific waste production, and local demographic, socio-economic influences:

$$P = inh \,.\, spec \,.\, std \,.\, sz \,.\, unemp \,.\, hsg \,.\, heat, \qquad (1)$$

where:
P is the amount of the MSW production of municipality per year in tons [t];
inh is the number of inhabitants of municipality;
spec is the specific waste production coefficient (reference values of other coefficients), measured in tons [t];
std is the standard of living coefficient;
sz is the size of the community coefficient;
unemp is the unemployment rate coefficient;
hsg is the type of housing (recreation, blocks of flats, empty houses, etc. coefficient and
heat is the type of heating coefficient.

The model (1) came with a finer division of demographic, socio-economic impacts on production and treatment of MSW at the level of individual municipalities. It enables us to meet the conditions required by the Ministry of Environment (MoE) to hit the regional dimensions (at least at district level) and, therefore, to meet different impacts on relative prices of waste management in different regions of the Czech Republic, see Hřebíček et al. [2010]. This model was investigated, calibrated and verified for three years in the South Moravian region of the Czech Republic, where some of the above variables were optimised by Hejč et al. [2008], Hejč and Hřebíček [2008a] with the simple expression:

$$x = (act / ref).\ cx,$$

where x means a variable from {*std, sz, unemp, hsg, heat*} and
ref means a reference value from three year investigations;
act an actual value from given year and
cx is the compensator (given by optimisation process) of the considered variable x.

The above model (1) calculates the production P_i of MSW in each municipality S_i based on the adjusted number of inhabitants inh_i, the specific waste production coefficient *spec* and specific demographic data reflecting the population behaviour with respect to MSW management (i.e. the type of housing hsg_i and other variables std_i, sz_i, $unemp_i$, $heat_i$ of municipality S_i), (i=1…N). These data are downloaded from publicly accessible registers of the Center for Regional Development of the Ministry for Regional Development of the Czech Republic and the Czech Statistical Office. They are updated annually from all municipalities in the Czech Republic; therefore, the model enables us to calculate the production of MSW for the given year with actual variables in (1) and predict waste production with using the linear model of the Waste Management Plan of the Czech Republic. We were able to calculate waste production MSW for the year 2008 and predict the increase of the production of MSW in 2016 and 2020 years.

The validation and optimisation of the model (1) outputs - the production P_i of MSW - was done by Hejč and Hřebíček [2008a] with the available data from the annual reports of municipalities S_i of the South Moravia region; however, annual reports of MSW of S_i bear some error, which arose from different data qualities. The process of the improvement of the data quality of municipalities S_i of the South Moravian region lasted several months. The data from the annual reports of all municipalities about their waste production are collected by the *Information System of Waste Management* (ISWM) of the Czech Republic. We used these, but we had to solve the problem without complete data, because more than 500 municipalities of the Czech Republic did not report their annual MSW production to ISWM. So we had to use the model (1) for the calculation of their missed MSW production in 2008 and the prediction of their MSW production in 2016 and 2020 years.

We have to estimate the MSW composition for the calculation of the amount of separated components of MSW at each municipalities S_i to obtain the rest PD_i of MSW P_i after the separation of recyclable components. We used for this estimation values listed in the Table 1, which are based on the results of research of Benešová et al. [2009] and Vrana et al. [2010].

Table 1. MSW composition at the Czech Republic (weight %)

Material	The share of material groups in waste (% by weight), average			
	Housing estates of big cities	Housing estates of small cities	Mix housing estates of cities	Rural area
Paper	22,7	22,2	25,6	7,6
Plastics	13,8	16,8	18,0	9,0
Glass	8,7	6,7	7,6	8,9
Metals	3,4	3,0	3,1	4,5
Bio-waste	18,2	19,6	17,3	6,3
Textile	5,6	6,6	5,1	2,2
Energy recovery waste	12,4	6,7	7,0	6,2
Under 20 mm	9,7	8,1	8,2	45,8
Other	5,5	10,3	5,1	9,5
Totally	100,0	100,0	100,0	100,0

We considered values from Table 1 to estimate real quantity of a disposable production PD_i of MSW from the municipality S_i to waste treatment facilities (new ones or available ones) after separation of recyclable components of MSW, which was estimated by Hejč et al. [2008], Hřebíček et al. [2010]:

$$PD_i = (1 - sep_i \,.\, will_i)\, P_i, \tag{2}$$

where sep_i is the ratio of separation at source S_i, $will_i$ is willingness to separate MSW (paper, glass, metals, textile and bio-waste) at municipality S_i (i=1…N). Coefficients sep_i and $will_i$ came from data of the investigation of the MoE and were validated in the South Moravian region by Hejč and Hřebíček [2008a], Hřebíček et al. [2010].

The model (2) helped us to solve some uncertainties stemming from the different state of population awareness about MSW management and estimate the amount of disposable production PD_i of MSW from the municipality S_i to appropriate waste treatment facilities. The MoE has used this model since 2009 after several months reviewing process by experts using Vrana et al. [2010] approach.

4. ECONOMIC MODELS FOR FACILITIES

We developed cost economic models for all types of facilities F_j (j=1…M), i.e. composting, biogas, MBT and ERP plants and landfills, Hřebíček et al. [2010]. These models are similar and we introduced this economic model for a generic facility F.

Calculate the price p of one t of the waste treatment at a new composting, bio-gas, MBT and ERP plant F. This calculation is based on the financial and economic analysis and financing methods for the measuring the efficiency of investment, see Valach [2006], etc. We used the *Net Present Value* (*NPV)* as the basic calculation method for the price p.

$$NPV = -I + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} \tag{3}$$

where

- I means an investment expenditures in facility F,
- CF_i means a cash flow generated in the period i,
- r means the discount rate and
- n means the lifetime of facility.

To calculate the price p is assumed that the NPV must be at the time of return positive. Thus the basic assumption was that we set the maximum acceptable *payback* period of investment I in the facility F. Then n = *lifetime* = *payback* in formula (2). If we assume that

$$CF_i = pK + B_i - C_i - u_i - j_i - E_i - T_i \tag{4}$$

$$T_i = t(pK + B_i - C_i - u_i - j_i - E_i - O) \tag{5}$$

Then price p is defined as

$$p = \frac{\dfrac{I}{(1-t)\sum_{i=1}^{n} 1\big/(1+r)^i} - B + C + \dfrac{\sum_{i=1}^{n}(u_i + j_i + E_i)}{\sum_{i=1}^{n} 1\big/(1+r)^n} - \dfrac{tO}{1-t}}{K} \tag{6}$$

where

- B_i is the total revenue generated from the facility in the period i,
- C_i is the total operating costs arising from the facility during the period i,
- K means the capacity of the facility,
- T_i means a tax on income arising from the facility during the period i,
- u_i means the interest due on loans for the period i,
- j_i means repayment of principal on loans for the period i and
- E_i means the costs of emission allowances for the period i.
- i means the period (year) from 0 to n
- n means lifetime and also payback of the facility

It is clear that different facilities will have different costs, incomes, investments, etc. For each-mentioned facility F_j (composting, bio-gas, MBT and ERP plants, and landfills) we developed economic sub-models for the construction of the price p_j of the given facility F_j (j=1…M). These models were based on the real level of investment, operating expenses, operating incomes, interest on loans, capacity of facility and emissions, Hřebíček et al. [2010]. The economic model of landfill was evaluated based on the average price of all landfills in the Czech Republic because the standard deviation of prices was less than 10 percent.

5. CARBON EMISSION MODEL

Reducing greenhouse gas emissions is an important social topic in the Czech Republic--particularly the suppression of landfill methane emissions. Total emissions of CO_2 equivalent will have to be significantly reduced in the waste management sector. In developing the carbon emission model, we have confined ourselves to minimise greenhouse gas emissions in the transportation, composting, incineration and land-filling MSW. Modelling of these emissions is a standard part of the LCA models of MSW management, so that in Solano et al. [2002], there are emission factors. This means that the emission factors, unit fuel consumption, energy prices, waste categorisation and other parameters are fixed set according to the Czech Republic where the IMWM was constructed. Moreover, users are not accessible to balance relationships, the models developed above do not optimise traffic and are strictly deterministic (do not take into account random variations of input data and uncertainty of adjustable parameters). Besides the mass-flow models, there are also above economic models that can describe the system of unit costs and to examine the impact of economic instruments; therefore, the carbon emission model was simply transformed into the above economic model by replacing the unit cost of emission factors. Because the model allows us to insert individual emission factors, which depend on the waste treatment technology and its optimal use, it is possible by analogy to conduct economic optimisation with regard to the cost of waste treatment facilities; however, the data for new facilities are not available to the regulator (MoE) and can be obtained only from the operators (or potential investors at prepared facilities) or expert estimations.

6. INTEGRATION OF SUB-MODELS INTO INTEGRATED MODEL OF WASTE MANAGEMENT

The above chapters introduced shortly four developed different sub-models needed for the regulation of waste management of the Czech Republic and a decision support of the allocation of subsidies from EU. We used properties of the MS Excel spreadsheet for the integration of above sub-models into one of the IMWMs for the Czech Republic to evaluate cost and price relationships for the municipal waste management of the country.

This implementation of IMWM enables the central option of the set of the input economic parameters of the model at the single control sheet of the MS Excel with interconnected sheets, where we implemented above sub-models:

a) the sheet (table) of socio-demographic variables inh_i, std_i, sz_i, $unemp_i$, $heat_i$, hsg_i, sep_i, $will_i$ of all municipalities S_i of the Czech Republic needed to calculate the outputs P_i and PD_i , (i=1…N), of the model (1), (2),
b) the sheet with the dynamically calculated the vector $\boldsymbol{dc}$ of the distance dc_i of source S_i from the closest landfill F_c by *Network Analyst* program, and the cost CTF_i of waste treatment of PD_i at the landfill F_c together with the cost CTE_i of transport to this facility including carbon emissions cost, (i=1…N),
c) the sheets of economic models (6) of (planned and current) waste treatment facilities F_j with dynamically calculated prices p_j including costs of carnon emission, (j = 1…M),
d) the sheet with dynamically calculated a potential amount of MSW from "the collecting waste area" of the facility F_j (j=1…M), where the collecting waste area consists of the municipalities, where are cheaper costs (CTF_i + CTE_i) to the closest appropriate facility than ones to the closest landfill,

e) the sheet of main communication interface the IMWM, where the input economic variables together with the allocation of new facilities are set up with further options required for the model.

Decisions makers of the MoE were able to use this IMWM to allocate subsidies from EU to investors of potential facilities to decline MSW from landfills to new facilities (ERP and MBT). They could choose inputs: *the list of K planned facilities* F_s (s = 1…K) (they are connected with their economic models); *their common payback; common value-added tax; chosen percentage of subsidy; charge of landfilling* and *landfill reclamation*. They obtained outputs of this model, where were *prices* p_s *of waste treatment* at planned *facilities* F_s, and calculated prices $CT_i = (CTF_i + CTE_i)$ for all municipalities S_i, (i=1…N) of the Czech Republic which will pay for the treatment of MSW.

7. CASE STUDY FOR ALLOCATION OF NEW FACILITIES

We will illustrate the IMWM application to monitor total cost and pricing relationships in waste management for the Czech Republic. The IMWM was applied to estimate price load per capita at every MSW source Si, (i=1…N) and total cost and pricing relationships in the waste management of the Czech Republic, depending on planned EU subsidies to new allocated facilities (ERP and MBT) including the total amount MSW declined from landfills to these facilities. The IMWM was used for 36 different scenarios of subsidy schemes to split the amount of subsidy of EU structured funds for the investment of 12 possible allocations of mechanical biological treatment (MBT) plants and incineration plants with energy recovery (ERP). We modelled: *total planned EU subsidies to new allocated facilities (ERP and MBT); the quantity of MSW which is available for each facility in comparison with its planned capacity; and the price load per capita (average and maximum) of MSW treatment for the Czech Republic*.

The Table 2 shows the outputs of the model, i.e. prices (in CZK – Czech Crowns) of waste treatment of 1 ton MSW at planned facility (ERP and MBT) of given capacity with respect to considered EU subsidies.

Table 2. Prices of waste treatment of 1 ton at facility and average price per capita.

	ERP capacity per year		MBT capacity per year		Price per capita
EU subsidy	100 kt	200 kt	80 kt	100 kt	average
20%	1 565 CZK	1 363 CZK	1 742 CZK	1 702 CZK	740 CZK
30%	1 328 CZK	1 137 CZK	1 638 CZK	1 596 CZK	733 CZK
40%	1 091 CZK	912 CZK	1 539 CZK	1 491 CZK	719 CZK

8. CONCLUSIONS

The integrated waste management model of the Czech Republic is introduced in the paper. The model was implemented with using MS Excel as the combination of the tools: GIS Network Analyser, sophisticated sub-model calculating MSW production and separation of its component at all municipalities of the Czech Republic, cost economic sub-models of all facilities including carbon emission.

It enables to optimise environmental impacts (land-filling and greenhouse emissions). Its application was used as the decision support tool of the MoE in the case study of optimising EU subsidies to the planning allocation of new waste treatment facilities (ERP and MBT) with respect to expenses per capita of waste management of the Czech Republic.

REFERENCES

Benešová, L., Hnaťuková, P., Černík, B. and Kotoulová, Z., Municipal Waste – Environmental and Social Problems in Future. In The Twenty-Fourth International

Conference on Solid Waste Technology and Management, Philadelphia, PA, U.S.A. (15.-18.3. 2009). 2009. http://komunalniodpad.eu/index.php?str=konference

Berger C., Savard G., Wisere A., EUGENE: an optimisation model for integrated regional solid waste management planning, *International Journal of Environment and Pollution,* 12(2/3), 280-307, 1999.

FreeGeodataCZ, http://grass.fsv.cvut.cz/wiki/index.php/FreeGeodataCZ

Haigh M. et al., EPIC/CSR Integrated Waste Management Tool: Environmental Analysis Model, Environment and Plastics Industry Council and CSR: Corporations Supporting Recycling, Version: Release 2.0.6., 2006.

Hejč, M., Hřebíček, J., Primary Environmental Data Quality Model: Proposal of a Prototype of Model Concept. In Proceedings of the iEMSs Fourth Biennial Meeting: International Congress on Environmental Modelling and Software (iEMSs 2008). Barcelona, Catalonia : International Environmental Modelling and Software Society (iEMSs), p. 83-90, 2008.

Hejč, M., Hřebíček, J., Environmental Reporting Information Quality in Companies of the South Moravian Region. In Sustainability Accounting and Reporting on Micro and Macro-Economical Level. Pardubice: University of Pardubice, pp. 59-63, 2008a.

Hejč, M., Horsák, Z., Hřebíček, J., Information Tools for Supporting Implementation of Integrated Waste Management System in the Framework of the Czech Republic. In EnviroInfo 2008. Environmental Informatics and Industry Ecology. Aachen, Germany : Shaker Verlag, p. 637-640, 2008.

Hřebíček, J., Friedman, B., Hejč, M., Horsák, Z., Chudárek, T., Kalina, J., Piliar, F., *Integrated waste management system at regional level* (in Czech), Littera, 202 p., 2009.

Hřebíček, J., Hejč, M., Soukopová, J., Analysis of Cost and Price Relationship in the Waste Management of the Czech Republic… (in Czech). Research report. Ministry of Environment of the Czech Republic. January 2010.

McDougall, F., Thomas, B. and Dryer, A., Life Cycle Assessment for sustainable solid waste management - an introduction. *Wastes Management*, May 2002, 43-45, 2002.

Network Analyst, http://www.esri.com/networkanalyst

Rathi, S., Optimisation model for integrated municipal solid waste management in Mumbai, India. *Environment and Development Economics* 12(1), 105–121, 2007.

Solano, E., Ranjithan, S.R., Barlaz, M.A. and Brill, E.D., Life-Cycle-based Solid Waste Management. I: Model Development. *Journal Environmental Engineering* 128(10), 981-992, 2002.

Shmelev, S. E., Powell, J. R., Ecological-economic modelling for strategic regional waste management systems, *Ecological Economics*, 59 (1), 115-130, 2006.

Valach, J., *Investment decisions and long-term financing* (in Czech), Ekopress, 2006.

Vrana, I. et al., A New Fuzzy Group Consensus-based Approach for Multi-aspect Environmental Decision Making. *Environmental Modelling & Software*. (to appear), 2010.

Wang F.S., Deterministic and stochastic simulations for solid waste collection systems – A SWIM approach, *Environmental Modelling and Assessment*, 6(4), 249- 260, 2001.

Yeomans J.S., Application of Simulation-Optimisation Methods in Environmental Policy Planning Under Uncertainty, *Environmental Informatics Archives*, 4, 167-185, 2006.