Modelling Integrated Waste Management System of the Czech Republic

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Abstract: The paper is devoted to environmental modelling, particularly modelling of Integrated Municipal Solid Waste Management Systems at the Czech Republic (IMSWMS). There are considered input macroeconomic variables (landfills fees, price of electricity, tax on incomes, percentage of subsidies, etc.) prescribed by the government regulator (Ministry of Environment). It enables to simulate the different scenarios of prescribed waste landfill fees, an inclusion or an exclusion of certain facilities of energy recovery / mechanical-biological treatment of waste with prescribed annual capacity in selected locations. It uses GIS Network Analyst for modelling municipal solid waste (MSW) streams among municipalities and waste treatment facilities. Quantity of the production of MSW are taken from annual reports of municipalities (if available) or estimated (if unavailable) by using a sophisticated model including demographic and socio-economic impacts. The is presented the case study of modelling changes IMSWMS in accordance with the implementation of the European Union Waste Framework and Landfills Directives into Czech legislation.

Key-Words: Environmental modelling, Municipal solid waste, Integrated waste management system, Waste management modelling

1 Introduction
Integrated municipal solid waste management system (IMWMS) consists of several stages (raw materials extraction, processing, sale, consumption, finally becoming waste when they are discarded by consumers. These materials in the waste stream then undergo collection, sorting (removal of recyclable materials) and treatment (which can be thermal or biological), with the final stage being disposal in the landfill. So we can define the individual waste streams, which are mass balancing.

Earlier this decade, the development of models of waste management systems began moving towards the IMWMS, which are designed to minimise the environmental impacts and/or economic costs, see [2], [4], [14], [17], [18]. Consider the IMWMS of the Czech Republic discussed by [8], [9], [10] which consists of the set of municipal solid waste (MSW) sources (municipalities) 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 waste material balance is examined in terms of waste material streams between MSW sources and waste treatment facilities.

Modelling IMSWMS has a complex nature with a range of important dimensions such as multiplicity of the types of waste generated in the communities, complex spatial pattern of waste arising, the necessity to transport waste long distances for processing, a variety of emissions from waste collection, transporting and treatment to the environment, and the almost unpredictable and localised character of impacts of these emissions on humans and ecosystems. And although there have been attempts to analyse the IMSWMS of the Czech Republic taking into account environmental impacts of processes under study, most of them have not formed a holistic method for analysing all spatial, temporal as well as qualitative aspects of the problem.

Therefore, the aim of the paper is to introduce a new methodological background for IMSWMS modelling of the Czech Republic, taking into account spatio-temporal patterns of waste generation and processing, environmental as well as economic impacts of the system development with a particular emphasis on public health and biodiversity.

In modelling the IMWMS of 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 [11], [13] and Fig. 1.
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, uncertainty of our model by the estimation of the composition MSW were calibrated with the database of collected data from annual waste reports of municipalities regarding the quantity and separated components of MSW.

We combine four sub-models in modelling IMWMS of the Czech Republic:

a) The transport sub-model of MSW flows among sources and facilities with using the geographic information system (GIS) ArcMap with its extension Network Analyst, [9], [10]. It computed the transport matrix linking the sources MSW and waste treatment facilities and enabled to find the closest facility to municipality. Further, the simple model, which is generated emissions from the transport of MSW. b) The waste production sub-model of [7], [9], [10] for the determination of the quantity and composition of MSW at every source (municipality). This quantity and composition MSW were calibrated with 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 waste treatment facilities including the generation of the emissions of MSW treatment, [10], [15].

d) The carbon emissions optimisation sub-model, which enables the choice of either the economic or the environmental point of view. 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.

The production of MSW at the Czech Republic is approximately 3,2 Million tons of MSW annually (in 2008), and most (85%) of it is landfilled. The Waste Management Plan of the Czech Republic (WMP) together with the Directive 1999/31/EC of 26 April 1999 on the landfill of waste (Landfill Directive) request to decline 1,5 Million tons of MSW from landfills to waste recovery facilities up to 2020 year.

The paper introduces above environmental modelling approach to offer decision support tools for the policymakers of the Ministry of Environment of the Czech Republic (MoE), which will help them to solve above problems using subsidies of European Union (EU).

2 MSW Streams Modelling

Consider the MSW streams at the Czech Republic among all sources (municipalities) \( S_i, (i=1...N) \), \( N = 6245 \) and all waste treatment facilities \( F_j, (j=1...M) \), \( M = 307 \), where \( M_L = 237 \) is the number of landfills. Consider these MSW streams 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 \( D = \{d_{ij}\}, (NXM) \), 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 \( dc = \{dc_c\}, (NX1) \) of the source \( S_i \) from its closest landfill \( F_c \), \( c \in \{1, ..., M\} \).

We have used the GIS program ArcMap 9.2 with its extension Network Analyst 9.2 [12] from ESRI for the analysis of the closest facility (e.g. landfills) to the individual sources (municipalities).

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, [3]. It incorporates an advanced connectivity transport model that can represent complex scenarios, such as multi-modal transportation networks.
3 Modelling Quantity and Composition of MSW

We used for modelling the quantity and composition of MSW in each municipality of the Czech Republic and the sub-model [5], [8], [15]. They described the sophisticated model of MSW production as the function of appropriate variables taking into account specific waste production, and local demographic, socioeconomic influences. This model 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 to calculate the production of MSW for the given year with actual parameters and predict waste production with using the linear model of the Waste Management Plan of the Czech Republic. We were able modelling the quantity of the 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 outputs - the production $P_i$ of MSW - was done by [6], [8] 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 of completeness data, because more than 500 municipalities of the Czech Republic did not report their annual MSW production to ISWM. So we had to model their missed MSW production in 2008 and predict their MSW production in 2016 and 2020 years, [10], [15].

We used the results of research of [1] for modelling MSW composition. It was needed for the calculation of the amount of separated components of MSW at each municipalities $S_i$ to obtain the rest $PD_i$ of MSW $P_i$, $(i=1...N)$ after the separation of recyclable components. We estimated the real quantity of 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 by formula

$$PD_i = (1 - sep_i \cdot will_i) P_i,$$

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 [6], [9].

The model (1) 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 approach from [16].

4 Modelling Costs of Facilities

We developed the cost economic models for all types of facilities $F_j$ $(j=1...M)$, i.e. composting, biogas, MBT and ERP plants and landfills, [9], [15]. These models are similar and we introduced this economic model for a generic facility $F$.

We calculated the price $p$ of one ton of the waste treatment at a new composting, bio-gas, MBT and ERP plant $F$, which was based on the financial and economic analysis and financing methods for the measuring the efficiency of investment and used the Net Present Value (NPV) as the basic calculation method for the price $p$. To calculate the price $p$ we assumed that the NPV must be at the time of return positive. Thus we set $n$ the maximum acceptable project payback period of total investment $I_T$ in the facility $F$.

Then price $p$ was calculated [10], [15] as

$$p = \frac{I}{(1-t)\sum_{i=1}^{n} \frac{1}{(1+r)^i}} - \frac{B + \sum_{j} (u_j + j + E_j)}{\frac{1}{(1+r)^n} - \frac{1}{1-t}},$$

where are

$I$ – size of actual capital expenditures, that is, the total investment $I_T$ without loan $U$ and subsidy $D$,

$r$ – discount rate,

$t$ – tax on incomes,

$O$ – annual linear depreciation,

$n$ – lifetime and also payback of the facility $F$,

$B$ – total revenue generated from the facility in the lifetime of facility $F$,

$C$ – total operating costs arising from the facility during the lifetime of facility $F$,

$K$ – capacity of the facility $F$,

$u_t$ – interest arising from loan $U$ for the period $i$.
\[ j_i \text{ – repayment of principal on loan } U \text{ for the period } i, \]
\[ E_i \text{ – costs of emission allowances for the period } i, \]
\[ i \text{ – period (year).} \]

It is clear that different facilities will have different costs, incomes, investments, etc. We developed the economic sub-model for each type of facility \( F_j \) (composting, biogas, MBT and ERP plants, and landfills). Therefore, we were able to construct the price \( p_j \) of MSW treatment at the given facility \( F_j \) \((j=1\ldots M)\).

**Example:** Modelling the price \( p \) of MSW treatment at ERP facility.

We consider the following inputs (variables) of sub-model: payback \( n \); total investment \( I \); operating costs \( C \); incomes from other products \( B \); annual depreciation \( O \); the loan \( U \) (in the model is considered 3 types of loans designed for modeling price).

**Operating costs** \( C = FC + VC \) of ERP plant consists of fixed and variable costs.

**Fixed costs** \( FC = FC_1 + FC_2 + FC_3 + FC_4 + FC_5 \) includes: \( FC_1 \) personnel costs (wages, social insurance, health insurance etc.), \( FC_2 \) repairs and maintenance costs; \( FC_3 \) monitoring and analysis costs, \( FC_4 \) land tenancy, rental equipment costs, and other costs \( FC_5 \).

**Variable costs** \( VC \) include costs associated with ERP operating: energy and gas costs; disposal of sewage water costs and material costs; costs of landfill, which include costs of landfill slag (cinder); costs of landfill of fly ash; and transport costs.

Structure of operating costs of ERP is shown in Fig 2.

The economic sub-models were based on the real level of investment, operating expenses, operating incomes, interest on loans, capacity of facility and emissions, [9], [10]. The economic sub-model of costs on MSW treatment of landfills was evaluated using statistical survey of 100 landfills of the Czech Republic. It is based on the average price of MSW treatment of investigated landfills because the standard deviation of prices was less than 8 percent.

5 Modelling Carbon Emissions

In developing the carbon emission sub-model, we have confined ourselves to minimise greenhouse gas emissions in the transportation, composting, incineration and land-filling MSW. We used emission factors [13] for facilities and transport, unit fuel consumption for transport, energy prices for energy production at ERP/MBT in economic sub-models and other parameters, which are fixed set according to the Czech Republic.

Besides the MSW material streams modelling, there are also above economic sub-models that can describe the costs of emission allowances of facilities using economic instruments (e.g. taxes). Therefore, the carbon emission sub-model was simply transformed into the above sub-economic models by replacing the unit cost of emission factors. The economic sub-models allowed us to insert individual emission factors, which depend on the waste treatment technology. Therefore, it was possible by analogy to conduct economic optimisation with regard to the cost of waste treatment facilities.

However, it was problem with the data for new facilities, because they were not available to the regulator (MoE) and it could be obtained only from the facility operators (or potential investors at prepared facilities) or by expert estimations [16].

6 Integration of Sub-models

The above chapters shortly introduced different sub-models needed for the regulation of IMSWMS of the Czech Republic and a decision support of the allocation of subsidies from EU for building new ERP / MBT facilities and decline MSW from landfills. We used properties of the MS Excel spreadsheet for the integration of above sub-models into one model of the IMSWMS of the Czech Republic.

This enabled us modelling cost and price relationships for the MSW management of the country through the central option of the set of the input economic parameters of sub-models at the single control sheet of the MS Excel with interconnected sheets, where we implemented above-sub-models:
a) the sheet of socio-demographic variables (inh, std, sz, unemp, heat, hsg, sep, will) of all municipalities Si of the Czech Republic needed to calculate the outputs MSW quantities Pi and PD, (i=1,…N), b) the sheet with the dynamically calculated the vector df of the distance of source Si from the closest landfill Fi by Network Analyst program [12], and the cost CTi of waste treatment of PD, at the landfill Fi, together with the cost CTE of transport to this facility including carbon emissions cost, (i=1,…N), c) the sheets of economic sub-models of (planned and current) waste treatment facilities Fi with dynamically calculated prices pi (2) including costs of carbon emission, (j=1,…M), d) the sheet with dynamically calculated a potential amount of MSW from “the collecting waste area” of the facility Fi (j=1,…M), where the collecting waste area consists of the municipalities, where are cheaper costs (CTF + CTE) to the closest appropriate facility than ones to the closest landfill, e) the sheet of main communication interface the IMSWMS, where the input variables (together with the allocation of new facilities are set up with further options required for the model.

The implemented model of the IMSWMS of the Czech Republic calculates the costs of MSW treatment at each municipality of the Czech Republic based on prices at the nearest treatment facilities including transport costs and carbon emission costs. If the cost of MSW treatment in the ERP / MBT facility is less than the cost of landfilling, so it is assumed that the MSW from the municipality will be treated in an appropriate ERP / MBT facility. If costs are higher so it assumed that either the MSW disposed of at the nearest landfill.

6 Case Study: Modelling EU Subsidies
The model was applied to estimate the price load per capita at every MSW source Si, (i=1,…N) and total cost and pricing relationships in the IMSWMS of the Czech Republic, depending on planned EU subsidies to new allocated facilities (ERP / MBT) including the total amount MSW declined from landfills to these facilities. Decisions makers of the MoE choose input parameters of the above model: the list of K planned facilities Fs (s = 1…K) (they are connected with their economic sub-models); their common payback n; common value-added tax t; chosen percentage P of subsidy D; charge of landfilling CL and landfill reclamation CR. The outputs of this model were prices ps of waste treatment at planned facilities Fs and calculated prices CTi = (CTFi + CTEi) of MSW treatment for every municipalities Si, (i=1,…N) of the Czech Republic [9]. The used model for 36 different scenarios of subsidy schemes to split the amount of subsidy of EU structured funds for the investment of K=12 possible allocations of projects of MBT / ERP plants.

Table 1 shows the example of part of outputs of the model, i.e. costs (in CZK – Czech Crowns) of 1 ton of waste treatment at planned facility of given capacity with respect to EU subsidies and average of price per capita of MSW treatment in the Czech Republic, which experts obtained for all scenarios and planned facilities.

Table 1. Costs of 1 ton of MSW treatment at facility and average price per capita (in CZK).

<table>
<thead>
<tr>
<th>EU subsidy</th>
<th>ERP capacity per year</th>
<th>MBT capacity per year</th>
<th>Price per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kt</td>
<td>1363</td>
<td>1363</td>
<td>1 702</td>
</tr>
<tr>
<td>200 kt</td>
<td>1 328</td>
<td>1 328</td>
<td>1 742</td>
</tr>
<tr>
<td>80 kt</td>
<td>1 137</td>
<td>1 137</td>
<td>1 565</td>
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<tr>
<td>100 kt</td>
<td>1 091</td>
<td>1 091</td>
<td>1 539</td>
</tr>
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7 Conclusion
The paper described modelling Integrated Municipal Solid Waste Management System of the Czech Republic with original developed model that consists of four sub-models, which allows the assessment of cost and price relationships in waste management of the Czech Republic in relation to several macroeconomic variables and variant assumptions about the cost of the above types of facilities (ERP, MBT and landfill), including the integration of these devices to system of emission trading EU ETS. The concept of the model is very general, and other additions and modifications of the model (e.g. addition of other relevant waste streams) will be performed on the current needs of its users from Ministry of Environment of the Czech Republic.

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