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Multi-objective Waste Network Flow Identification Model Based on Economic and Environmental Aspects

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Waste management demands continuous enhancement of existing infrastructure in terms of newly designed facilities which have a lesser impact on the environment. The transportation of waste and its further treatment in the facility should be optimised according to the cost and environment policy. The future planning of new facilities and transportation routes require complex information about current state of the waste operation activities. The legislation of the Czech Republic (also other countries with well-developed waste management) forces waste operators to register production, treatment and handling of waste. Such an information, stored in large databases, provide authorities with at least basic knowledge about the waste flows in the area. Additionally, the annual data reporting decreases the information about producers' waste flow due to the aggregation, inconsistency and/or inaccuracy (low quality of reported data). This paper presents an approach for flow and treatment identification based on the combination of data reconciliation with economic and environmental aspects. The approach uses mathematical programming techniques for identifying errors in the database with regards to the network flow preserving continuity and balances between and in the nodes. The objective is to make the amount of produced and delivered waste to each node equal to the amount that was there processed or removed. This is required with the minimum modification of the input data. Weights are introduced to distinguish high and low-quality data by assigning bigger values to arcs where sent amount correspond with quantity received. The results of this analysis provide an assessment of current waste handling for the particular node, which forms an essential information for future planning of processing facilities and their technologies. The multi-objective model considers environmental aspects as relations between treatment options and transportation distances (cost). Longer transportation distances are tolerated for higher treatment options in the waste hierarchy. The presented model has been tested through a case study on the database of waste management in the Czech Republic. The network was considered on the regional level. However, any commodity, which is included in supply chain models and has a reporting obligation, can be handled in a similar way. Further research might be focused on possible extensions such as influence from stakeholders in decision-making which provides proved flow inputs.

1. Introduction

Nowadays, a large number of different kinds of waste is produced. In order to design new waste disposal and treatment facilities that are economically and environmentally friendly, the comprehensive information about the current situation is needed. For example, Zheng et al. (2017) provide information about construction and demolition waste in China. Margallo et al. (2014) assess the impact of municipal solid waste incineration on the environment. The information is especially important while assessing the composition of waste, the environmental impact and choosing the right recycling technology. However, the provided information about the composition and the possibilities of waste treatment is not sufficient. It is necessary to include the current waste flow to realise future planning of new facilities and transportation routes. Lee et al. (2016) focus on waste flows between collection points, incinerators, landfills and replacement truck warehouses. In general, the basic knowledge about the waste flows in the area is stored in the large database. However, inputs are often

inconsistent and/or inaccurate due to the poor quality of reported data which is caused by bad records, tax documents, etc. For this reason, the data needs to be verified and balanced prior to its use in supply chain model. Regarding technical applications, the framework for data reconciliation using fuzzy set theory is proposed in the paper (Džubur et al., 2017), where the physical relationships are used to form constraints. In other paper (Cencic, 2016), the nonlinear data reconciliation was performed, based on the conventional weighted least-squares minimization approach and error propagation.
Both the economic and environment criterions are important, due to the distance between producer and processing plant. Emara et al. (2016) minimize total costs, including shipping, while the facility for biomass treatment is located. Struk (2017) examined whether the waste separation is economically beneficial with regard to distance. On the other hand, environmental protection is also important, especially nowadays when the industrial production increases. Tascione et al. (2016) describe the waste management environmental impact using data from Life Cycle Assessment. The environmental impacts of the particular type of waste are presented in the manuscript (Bogocka et al., 2017).
However, the situation is much more complicated within the socio-economic sphere. There are no natural laws to follow, but certain rules can be used. For example, the average person is mostly expected to choose cheaper alternative but an emotional role in the form of an environmental impact is also accounted. All the previously mentioned approaches have been dealing with the future planning and processes optimisation. An accuracy and credibility of the input data have never been guaranteed and dealt with. The new approach uses the ideas of Šomplák et al. (2017b) which presented identifying errors in the database and Šomplák et al. (2017a) who determined the flow within the network with uncertainties, arising from incomplete or unknown information. Connecting both approaches (balancing data in the database and assuming that the producer transports waste to the nearest processing facility) contributes to more realistic results of data verification. Waste producers behave economically. The presented mathematical model (see section 2) estimates the current state of waste management and finds out where the waste from a particular producer was processed while preserving continuity in the network flow. It concerns also balance in nodes and transportation distance to be the shortest possible. Information about treating waste is available in the database. Treatment methods are considered according to Directive 2008/98/EC on waste. It is suggested in this paper, the environmental friendly treatment is realised, the longer transport distances are tolerated. The proposed relation of two approaches is based on optimization methods to identify errors in the large database while considering the distance between waste producers and processing facilities. The model for waste flow identification is applied to the data of the Czech Republic in the case study in section 3.

2. Mathematical model

The presented model was created for the application of waste management in the Czech Republic. Here is a public database where waste streams can be found. Flow is always reported by both waste sender and waste receiver. For this reason, two scenarios are considered in the model: for sending marked by (-) and for receiving (+). None of these scenarios is preferred because information about the more accurate scenario is not known. The model also takes account of waste treatment methods and prefers shorter distances for transport for both economic and environmental reasons.

Sets:

$i, p \in I$	nodes (producers)
$j \in J$	arcs
$l \in L$	waste treatment options

Parameters:

$x_j^{\pm}$	amount of waste shipped on arc j according to the scenario + or – (carry to / take away)
$A_{i,j}^{\pm}$	incidence matrix for the scenario + or –
o_i	waste production in the node i
$t_{i,l}$	waste treatment type l in the node i
w_j	weight of the arc j, $w_j \in (0; 1)$
d_j	length of the arc j
a	threshold of zero penalization
W	weight of penalization
β	weight of objective function
M	big enough constant
$\delta_{i,p}$	binary operator $\begin{cases} 1 \text{ if } i = p \\ 0 \text{ if } i \neq p \end{cases}$
z_1^*, z_2^*	optimal objective function values

Variables:

z_1, z_2, z_3	objective functions
τ_i	error in the production in the node i
y_i	penalization
$\varepsilon_j^{\pm}$	error on the arc j according to the scenario + or -

Positive variables:

$\varepsilon_j^{\pm\pm}$	positive or negative part of the error ε_j^+ or ε_j^-
$t_{i,p,l}^P$	treatment of the waste in the node i from the producer p type l

$x_{j,p}$	amount of shipped waste from the producer p on the arc j	$y_i^{\pm}$	positive or negative part of the penalization y

$$z_1 = \sum_{j\in J}(\varepsilon_j^{-+} + \varepsilon_j^{--} + \varepsilon_j^{++} + \varepsilon_j^{+-})w_j + W\sum_{i\in I}(y_i^{+} + y_i^{-}) \quad (1)$$

$$z_2 = \sum_{j\in J}\sum_{i\in I} d_j x_{j,i} + W\sum_{i\in I}(y_i^{+} + y_i^{-}) \quad (2)$$

$$z_3 = \frac{\beta z_1}{z_1^*} + \frac{(1-\beta)z_2}{z_2^*} \quad (3)$$

s.t.

$$o_i + \tau_i - \sum_{p\in I}\sum_{l\in L} t_{i,p,l}^{P} - \sum_{p\in I}\sum_{j\in J} A_{i,j}^{-}x_{j,p} + \sum_{p\in I}\sum_{j\in J} A_{i,j}^{+}x_{j,p} = 0 \quad \forall i \in I, \quad (4)$$

$$t_{i,l} = \sum_{p\in I} t_{i,p,l}^{P} \quad \forall j \in J, \quad (5)$$

$$o_p + \tau_p = \sum_{i\in I}\sum_{l\in L} t_{i,p,l}^{p} \quad \forall p \in I, \quad (6)$$

$$\sum_{j\in J} A_{i,j}^{+}x_{j,p} + \delta_{i,p}(o_i + \tau_i) = \sum_{j\in J} A_{i,j}^{-}x_{j,p} + \sum_{l\in L} t_{i,p,l}^{P} \quad \forall i,p \in I, \quad (7)$$

$$x_j^{+} + \varepsilon_j^{+} = \sum_{i\in I}\sum_{p\in I} A_{i,j}^{-}x_{j,p} \quad \forall j \in J, \quad (8)$$

$$x_j^{-} + \varepsilon_j^{-} = x_j^{+} + \varepsilon_j^{+} \quad \forall j \in J, \quad (9)$$

$$x_j^{-} + \varepsilon_j^{-} \geq 0 \quad \forall j \in J, \quad (10)$$

$$o_i + \tau_i \geq 0 \quad \forall i \in I, \quad (11)$$

$$\varepsilon_j^{-} = \varepsilon_j^{-+} - \varepsilon_j^{--} \quad \forall j \in J, \quad (12)$$

$$\varepsilon_j^{+} = \varepsilon_j^{++} - \varepsilon_j^{+-} \quad \forall j \in J, \quad (13)$$

$$y_i = \mathrm{sgn}(a)(\tau_i - a o_i) \quad \forall i \in I, \quad (14)$$

$$y_i = y_i^{+} - y_i^{-} \quad \forall i \in I. \quad (15)$$

There are three objective functions Eq(1-3) in the model. They are applied as follows. First, the objectives Eg(1-2) are calculated separately and minimised with different constraints. Eq(1) uses the constraints (4) to (14). The goal is to minimize the weighted total error on the arcs j and the sum of penalizations. Eq(2) minimizes the total distances to which the waste is transported with constraints (5), (6), (10), (14), (15). This results into two objective function values z_1^* and z_2^*. Further, their reciprocal and weighted (β) values are used as the weights in the objective function Eq(3). Parameter β determines which of the previous approaches (models with Eq(1) or Eq(2)) will be prioritized in the final model while minimising Eq(3). In this case, all constraints are used.
Eq(4) describes the conservation of the mass at each node, i.e. the sum of the amount of produced waste in the node i and the delivered waste to the node i (from all other nodes and from all the producers p) equals the sum of the treated waste in this node (from all producers) and the amount of waste taken away. Eq(5) says that the total amount of treated waste in the node i is equal to the sum of the treated waste from all producers. Eq(6) indicates that all produced waste from the producer has to be treated somewhere. The next equation is a condition that everything that comes to the node and what is produced there has to be taken away or treated. Eq(8) describes that the total amount of carried waste equals to the sum of the amount of imported waste from the individual producers. Eq(9) ensures the equality of both scenarios (what has been taken away has to be carried). Eq(10) and Eq(11) express non-negativity of the amount of waste stream and the amount of waste production. Eq(12) and Eq(13) divide the error to the positive and negative part. Eq(14) describes the calculation of the penalty. The threshold of zero penalty is determined similarly as in paper Šomplák et al. (2017). The last Eq(15) divides the penalty into the positive and negative parts. Weights w_j are introduced to distinguish high and low-quality data by assigning bigger values to arcs where sent amount correspond with quantity received. Longer distance for material recovery is accepted when environmental benefits of recycling are expected.
Weight w_j was introduced because of the data inconsistency. It can be calculated according to the Eq(16). More similar data are valued with greater weight. For example, if one node reports that it sends a large amount of

waste to the second node, but the other node has received a small amount (based on the database), there is probably an error, and the data cannot be trusted.

$$w_j = \begin{cases} M, & x_j^-, x_j^+ = 0 \\ \frac{\frac{x_j^- + x_j^+}{2}}{\left| x_j^- - x_j^+ \right|}, & otherwise \end{cases} \qquad \forall j \in J \tag{16}$$

The results of this analysis provide an assessment of current waste handling for the particular node, which forms essential information for future planning of processing facilities and their technologies.

3. Case study

The case study was based on data from the Ministry of the Environment of the Czech Republic. The aggregation of 206 micro-regions was used to form input data. It regards mixed municipal waste and comes from 2015. With the minimal modification of the input data, the balance in the nodes is ensured, i.e. the amount of produced and delivered waste of each node equals to the amount that was there treated, disposed of or sent elsewhere. In this study, the 14 regions are considered as individual nodes. Longer distances are accepted in the preferred mode of waste treatment. In this case, the material recovery, energy recovery, export, pre-treatment, disposal and other way of processing are distinguished.

The results of this analysis provide an assessment of current waste treatment at a particular node, which is the basic information for future planning of processing facilities and their technologies. Figure 1 shows the result of the calculation, where the treatment method of produced mixed municipal waste (MMW) is determined for all regions.

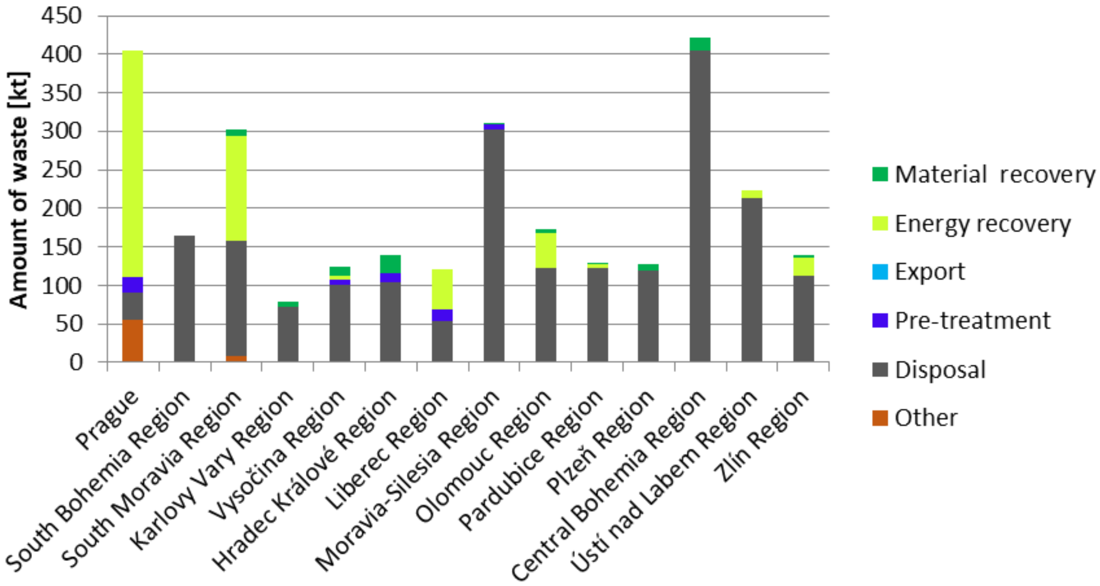

Figure 1: The amount of waste according to ways of treatment in the various regions

The obtained results also contain the information of how the waste is transported across multiple regions (import and export) based on the specific facility location. For example, Prague treats most of the produced waste (ca. 400 kt) on its own, however around 30 kt are exported to Liberec, Ústí and especially Central Bohemian regions. On the other hand, ca. 10 kt are imported from Vysočina Region due to a preferable treatment option.

Figure 2 shows percentage expression of the amount of treated waste. It clearly reveals all regions, where Waste-to-Energy plants were operated in 2015 (Prague, South Moravia and Liberec regions). Furthermore, the export of waste from Olomouc and Zlín regions to WtE in South Moravia Region is also evident (see the following detailed analysis). The most common method of waste treatment is disposal which is shown in grey (landfilling, incineration). In most regions, it is more than 90 % and altogether 2,071 kt were disposed of in the Czech Republic in 2015.

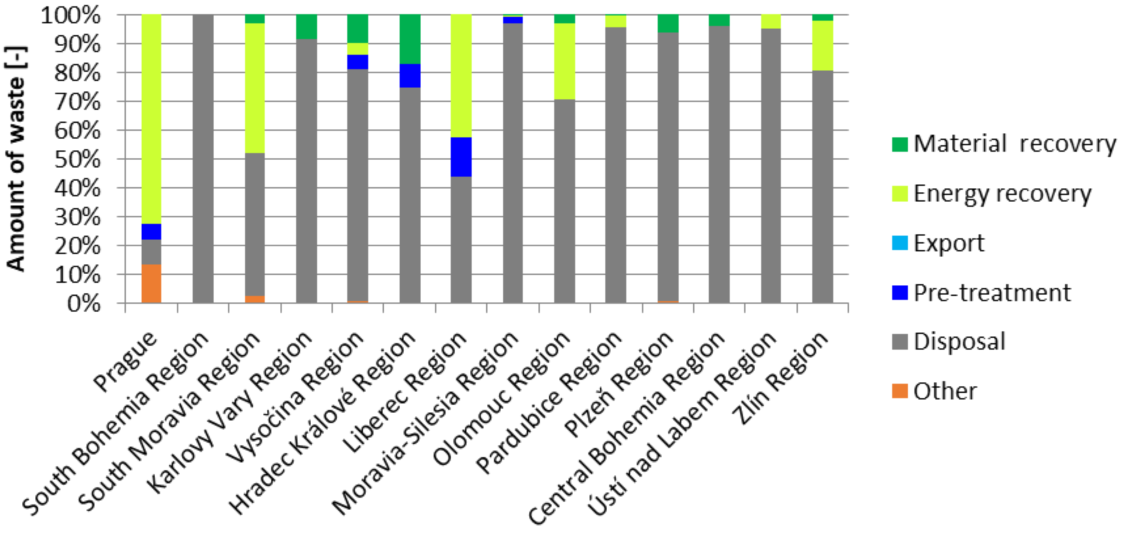

Figure 2: The percentage expression of the amount of waste according to ways of treatment in the various regions

Furthermore, the location where the waste was transported represents another result of the calculation. To provide comprehensive results, the South Moravia Region was selected. The graph in Figure 3 shows that most of the waste which was treated in the South Moravia Region comes from the same region. This corresponds to the mathematical model and the assumption that the waste is transported at the shortest distance. There is an effort to treat the waste in the region where it was produced. Waste to the South Moravia Region was also transported from the Olomouc and Zlín regions. The map shows that these regions are adjacent. The distance to which the waste was transported is therefore coherent.

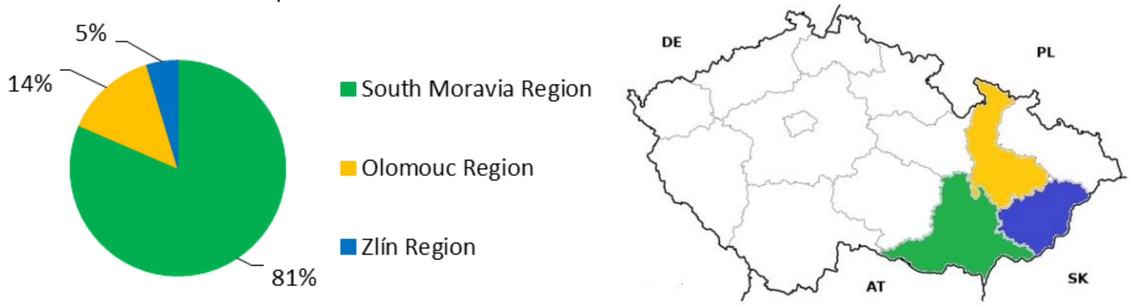

Figure 3: The regions from which the waste was treated in South Moravia Region and location of the regions

Figure 4 shows how was the waste treated in the South Moravia Region. The following methods of treatment were used in this region: material and energy recovery, disposal and other. The waste produced in the South Moravia Region was in this region either energetically recovered (136 kt) or disposed of (127 kt). Only 8 kt was processed in a different way. The waste from the Olomouc Region was also transferred to this region. All of this waste was recovered to produce energy and the same applies for most of the Zlín Region waste; a small part of the waste was used for material recovery. The waste transferred to the South Moravia Region is therefore well used. It is not desired to transport the waste for less preferred treatment methods (pre-treatment, disposal, other).

The results are quite similar for all regions. The transfer of waste to another region is realized mainly for material and energy recovery. In some cases, waste has to be transferred also for other ways. The results meet all the objectives (economic and environment) and so it can be assumed that the model is well designed. To certainly verify the results, the actual data at the higher level of detail (i.e. from micro-regions and individual producers to companies active in the field) is needed.

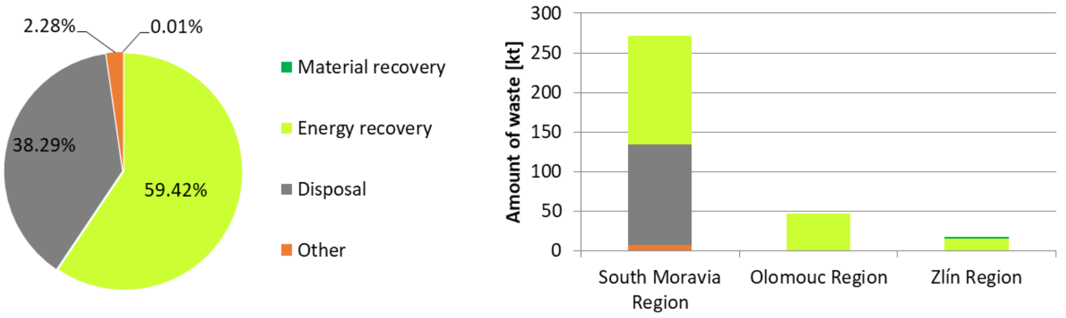

Figure 4: The percentage treatment methods in the South Moravia Region and distribution among regions

4. Conclusions

This paper introduces a mathematical model that can help in the future planning of new facilities and transport routes. The tool was tested for data from the year 2015 for the Czech Republic, where individual regions were selected as nodes. A data balance has been done because the database of waste management contains errors and inaccuracies. It was assumed that the waste was transported to the shortest possible distance. This is advantageous from an economic as well as ecological point of view. The price for both fuel and toll is lower and the amount of greenhouse gas emissions is reduced. The results show that the most of the MMW in the Czech Republic is disposed of. And so, there is a large potential for improvement – more waste for material or energy recovery. Further research might take into account the ownership of treatment facilities and transport companies. It is assumed that the transport company would transfer the waste to longer distances if the treatment facility has the same owner. The calculation with large dataset would require the use of heuristic algorithms presented by Viktorin et al. (2016).

Acknowledgments

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