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Network Flow Based Model Applied to Sources, Sinks and Optimal Transport of Combustible Waste

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Waste management has been an expanding field, which demands continuous enhancement by waste transportation and treatment capacities optimisation. Reuse and recycling is a preferred option as much as it is applicable. A new strategy is proposed and analysed compared to the current state. Presently the waste treatment is a key information for effectivity assessment of a newly designed system. The known parameters are usually: production (sources) and processing (sinks) of given combustible waste in specific territory unit (node) from considered area and transportation between these nodes. For real life data analysis, available information is production and different ways of treatment (according to the waste hierarchy). Transportation between the nodes is not always evident, which can lead to a lack of knowledge of the total cost and expenses for individual producers. To gather information, it is necessary to obtain and assess available data. This research presents a tool for pre-processed data where the potential for combustible waste suitable for energy recovery and/or recycling in pre-defined nodes is determined. The tool is based on the reverse logistic problem, which is a specific case of supply chain model. The objective is to optimise the system of network flow of unusable products from the producer to the treatment facility. It describes an approach to determine the flow of the network with the utilisation of uncertainties, arising from incomplete or unknown information. Decision-making is done in relation to transportation distance criterion. This criterion naturally prefers closer treatment facilities instead of more distant. In order to reflect the uncertainty in the decision-making process, a probability function that links preferences for the particular type of waste is implemented. Developed mathematical model gives an estimation of mean value for a decision variable (potential for energy recovery) and also provides additional information about variability for each node. As a result of this analysis, an assessment creates a distribution function for the amount of waste for specific processing in particular node. The potential for energy recovery depends on the amount of combustible waste, which is currently landfilled and not used for recycling. These data outputs are further used for prognosis and form the necessary foundation for the planning of future treatment facilities. This tool has been tested through a case study involving the particular stream of combustible waste (network with 206 nodes). It has been found that it is suitable for various applications. The results of the optimisation can also provide a guidance for GHG (greenhouse gas) footprint reduction. However, any commodity, which is included in supply chain models can be handled in a similar way. In further research, possible extensions for the presented tool are additional criterions, i.e. more specific transportation cost, waste treatment cost criterion or influence from stakeholders in decision-making.

1. Introduction

Many eastern and central European countries are undergoing a change in waste management. A new infrastructure for waste processing is being planned and built, to become consistent with the well-accepted

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hierarchy of waste management. The network flow models are commonly used in the supply chain for decision-making in many fields, e.g. (Qiu et al., 2015) utilised modelling for support in agriculture. Roupec et al. (2013) developed a hybrid algorithm, which combines a genetic and a traditional optimisation approaches. A mixed-integer (0-1) linear computational problem in the field of the transportation network design problem is described and solved for general product supply chain. Besides that, a great deal of different attitudes and techniques for waste management planning have been created. In this case, a reverse logistic problem is considered. Biswas and De (2016) considered a fuzzy chance-constrained programming approach is used for management of municipal solid waste (MSW) to minimise the network system cost. They minimised the cost of sorting and transporting the waste and considered different treatment facilities to maximise revenue. The facility allocation problem for biomass treatment was studied in by Emara et al. (2016), where total cost including transportation, fixed and handling cost, were minimised. The environmental impact of waste management based on LCA was analysed by Tascione et al. (2016). Šomplák et al. (2015) use network flow model to analyse the variability and probability of future cost of waste treatment for municipalities (producers of waste). Šomplák et al. (2014) were concerned with the appropriate location of processing plants using a transportation problem formulation. The key sustainability factor in the infrastructure planning of new projects is the availability of waste, as was analysed in (Ferdan et al., 2015).

All the research mentioned above make an effort to optimise the overall management. New arrangements are proposed based on minimised future processing cost. But none of the work compares expected cost with the current state. It is obvious since authorities do not always provide complete information about waste management (transportation and treatment methods). Consequently, identification of total cost and expenses for treatment in the particular node is problematic. As shown in this article, this pre-processing represents a complex independent task. In addition, an unambiguous commodity (waste) production is commonly expected, which could be a strong simplification especially when dealing with waste and considering different treatment methods. In this respect, the availability of biomass and demand of biofuel are utilised as a stochastic parameter in (Yue and You, 2016), to ensure the robustness of operational decisions.

Let us start with the following simplified example, which was inspired by current practice in reporting the waste management data in the Czech Republic. It is believed, that comparable reporting systems are also maintained in other countries not only for waste but also for other commodities. The production and treatment of waste are specified. However, the processing capacities may differ from the production in the particular node and even though, it is not guaranteed that the waste is treated locally. As a result, transport of waste between nodes is inevitable and even uncertain (Figure 1). Figure 1a) shows the input data – production and treatment. For mass balance fulfilment is necessary to transport waste among nodes. Figure 1b) and c) illustrate two possible options of the result. It can be observed that infinite feasible solutions exists (i.e. all the produced waste is appropriately treated).

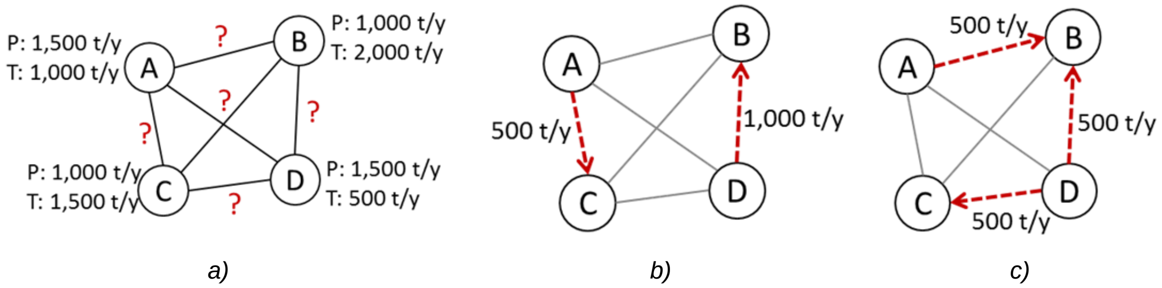


Figure 1: The schematic illustration of the available data and the problem of ambiguous solution flows. Where T - Treatment, P - Production

This paper considers the transportation distance as the criterion to determine waste flow in an investigated areas (see section 3). More specifically, a network flow model has been proposed, which helps to identify current flows between producers and processors. The main idea behind the approach is the minimisation of transportation distances and thus related transportation cost. An additional complication is a multitude of waste treatment methods and their prioritising (discussed in the following section), which is handled by the generation of the alpha parameter from triangular density function. Section 3 introduces the mathematical model and generation of the alpha parameter. In the case study in section 4, the model is applied to determine the real potential for Waste-to-Energy (WtE) treatment in the Czech Republic.

2. Preferred treatment options

From the perspective of an illustrative example of the previous section, the problem is further complicated when more treatment methods are considered. For waste, it is depicted in Figure 2, where treatment codes are used according to directive 2008/98/EC on waste. For demonstration let us divide the treatment into two types - T1 and T2 (see Figure 2). In the T1 option, reuse, recycling and material recovery are considered. The T2 encompasses energy recovery and disposal.

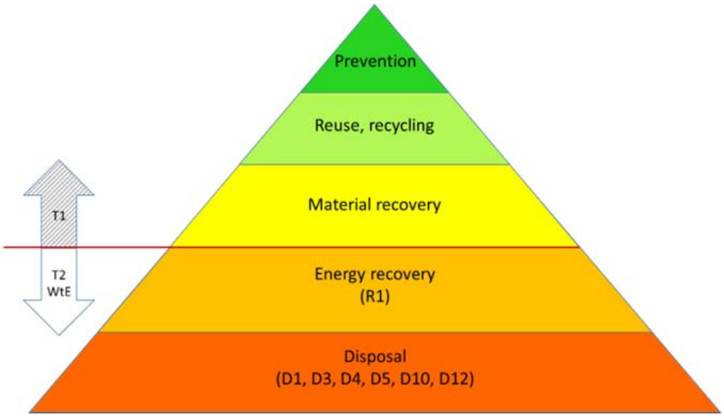


Figure 2: The waste management hierarchy and definition of potential for thermal treatment

The waste which is in Figure 1 considered for "treatment" is thus divided into the waste treated as T1 (mainly material recovery) and T2 suitable for WtE (T2 - see a list of treatment codes above). The utilisation of waste as an alternative fuel is analysed in Fodor and Klemeš (2012). The environmental impact of WtE is assessed in Tabasová et al. (2012). In the same way, waste produced in particular node (P) is divided according to its T1 or T2 treatment. This leads to the possible estimation of the potential for reverse logistic problems as mentioned in Section 1. Only a portion of overall production is considered for optimisation. Waste currently recovered as a material (T1) is not considered for optimisation of incineration capacities.

3. The mathematical model

Presented mathematical model considers two possible treatment options, T1 and T2, as described in the previous section. The notation used.

Sets

$i, j \in I$	index of the node
$s \in S$	index of the scenario

Variables

x_{ij}	amount of the transported waste for T1 from the node i to j
y_{ij}	amount of the transported of waste for T2 from the node i to j

Parameters

d_{ij}	distance between nodes i and j
P_i	production of waste in the node i
$T1_j$	treatment T1 (usage of waste) in the node j
$T2_j$	treatment T2 (removal of waste) in the node j
A_{ij}	adjacency matrix
α_i	probability weight for the node i

The developed mathematical model for purpose of this article consists of the following equations.

$$\min \sum_{i \in I} \sum_{j \in I} \alpha_i d_{ij} x_{ij} + \sum_{i \in I} \sum_{j \in I} (1 - \alpha_i) d_{ij} y_{ij} \tag{1}$$

s.t.

$$\sum_{i \in I} A_{ij} x_{ij} = T1_j \qquad \forall j \in I \tag{2}$$

$$\sum_{i \in I} A_{ij} y_{ij} = T2_j \qquad \forall j \in I \tag{3}$$

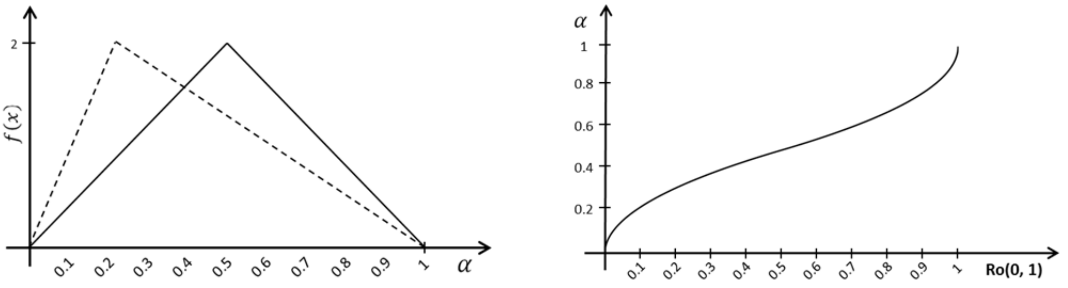
$$\sum_{j \in I} A_{ij} (x_{ij} + y_{ij}) \leq P_i \qquad \forall i \in I \tag{4}$$

$$y_{ij}, x_{ij} \geq 0 \qquad \forall i, j \in I \tag{5}$$

The objective function Eq(1) minimises the transportation distance (cost) between the x_{ij} and y_{ij} using the weight α_i. Constraints Eq(2) and Eq(3) give the restriction to the number of transported units of waste for treatment options, and makes them equal to $T1_j$ and $T2_j$. The constraint Eq(4) restricts the amount of transported units of waste to be less or equal to the production P_i. Eq(5) set the flows as nonnegative variables. In the real-life situation, the waste from producers do not always follow shortest transportation distance, i.e. the optimal transport assumption is violated. A random variable α_i is introduced. For α_i equal to 0.5 there is no preference between T1 and T2. For α_i, lower than 0.5 T1 is preferred. For α_i, higher than 0.5 T2 is preferred. Any value except 0.5 means, that there are longer transportation distances. The model Eq(1) to Eq(5) is applied within a loop over the scenarios that set the parameter α_i according to further function:

$$\alpha_i = \alpha_{is}, \qquad (6)$$

where s describes different scenarios. In each scenario and for each region, a random value for α_{is} was generated according to Figure 3. Figure 3a introduces the triangular probability density function. The peaks may be selected arbitrarily. Due to technological processing capabilities, it can be a tendency for certain waste to carry over greater distances because of hierarchy preference.



a) triangular probability density function

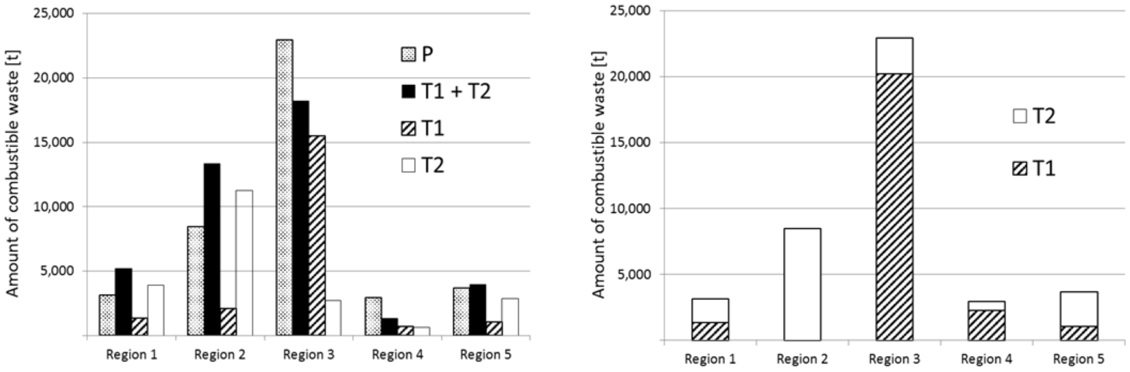
b) generating α value

Figure 3: The generation of α parameter for individual scenarios

With peak, less than 0.5 short distances for T1 are preferred. In other words, longer distance for material recovery is accepted, which is in line with expected environmental benefits of recycling compared to other options. In section 4, the symmetric function not to prefer any option is implemented. In Figure 3b, density function with the peak in 0.5 was transformed into a logarithmic function for random generation purposes.

4. A case study – combustible waste

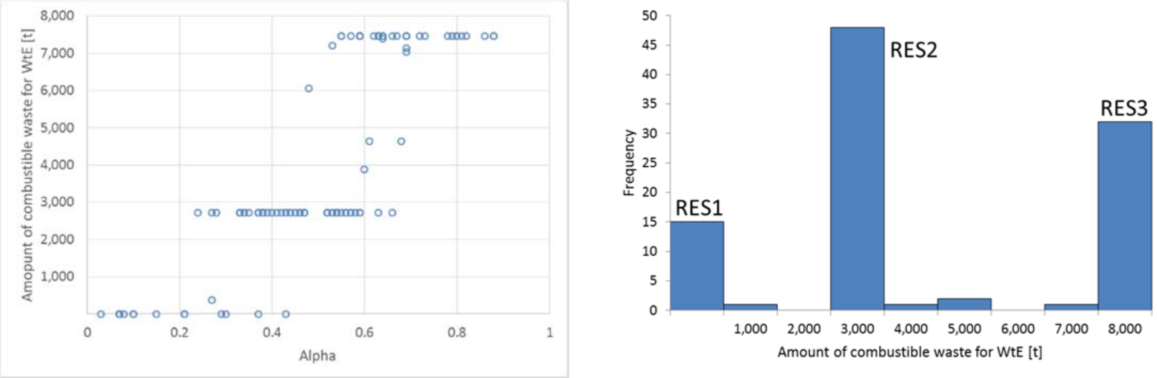
From the planning of processing infrastructure point of view, the information about current state of production and treatment is crucial. This paper deals with the specific type of waste – combustible waste (CW). The CW that is treated in higher priority level (prevention, reuse or recycling) in the waste management hierarchy (see Figure 2), is not preferred for WtE. On the other hand, the waste from T2 creates the potential of WtE recovery. The case study deals with transport identification of overall amount of CW between nodes, excluding MSW and bulky waste. These have to be examined individually. Based on data provided by the Ministry of Environment, the production of CW was ca. 3.2 Mt (100 %) in the Czech Republic in 2015. The major of this waste was materially recovered, approximately 2.44 Mt (76.2 %). A smaller portion, 0.435 Mt was recovered for energy production (9.6 %) or disposed of in landfills (4 %). The rest of the waste (10.2 %) was transferred abroad and there is no information available about treatment method. The total is balanced i.e. the production equals treatment and export. With regard to Figure 2, the potential of CW in 2015 for WtE was 0.435 Mt, which is a sum of energy recovery (R1) plus disposal codes. The issue is, in which regions (nodes) is this waste allocated and what are current transport distances to the places of its treatment. The main problem is the confluence of different streams of the same waste code in the particular node and their subsequent branching. This feature loses information about the waste source at individual nodes. To demonstrate the severity of the problem, see Figure 4, where 5 of 206 regions of the country were selected for illustration. The available information is only about production (source) and the amount of waste treated by a particular method (sink) at individual nodes (see Figure 4a). This figure shows the necessity of export of waste in regions 3 and 4. In contrast, the waste was imported into the regions 1 and 2. Region 5 seems to be self-sufficient, i.e. the production is about equal to the treatment. For regions 1, 2, 3, and 4, there is completely missing information about how (T1 or T2) and where the locally produced waste was treated. Even when the waste production equals to waste treatment, it is not guaranteed that part of the waste was not exported beyond the region and vice versa the same amount imported from other regions. However, due to transport distance, it is preferred to process the waste in the vicinity of the producer (see section 3 with mathematical model). The goal is to determine location and treatment method. The result for selected regions 1-5 and α_i equal to 0.5 (the case when there was no preferred way of treatment in terms of transportation distances) is shown in Figure 4b).



a) *Input data* b) *Treatment as a result of calculation*

Figure 4: Treatment of CW in selected regions in 2015

According to section 3, simulations with 100 scenarios were performed to determine the sensitivity of the entire system. The results of simulations with randomly generated parameter α_{is} for region 3 are shown in Figure 5. The production in region 3 is ca. 0.23 Mt. Figure 5a) shows the dependency of waste potential for the WtE plant on the selected parameters α_{3s}, which were generated as shown in the Figure 3b). Whereas symbol is generated from a continuous function, the results suggest only three possible scenarios in values 0 (all waste materially recovered, RES1), ca. 2,700 (RES2) and 7,500 (RES3) t in 2015 (see Figure 5b).



a) *Point graph* b) *Histogram*

Figure 5: Potential for WtE plants in region 3

The results of the analysis provide useful information about waste flows, i.e. transportation distances for individual regions. Table 1 shows five selected regions and the impact of processing site (sink) on the average transported distance of CW.

Table 1: Traffic parameters for 1 t of CW

	$\alpha = 0.5$			Average value		
	T1 [km]	T2 [km]	Total [km]	T1 [km]	T2 [km]	Total [km]
Region 1	0	0	0	19	2	21
Region 2	0	0	0	25	2	27
Region 3	17	0	17	23	14	37
Region 4	17	0	17	17	8	25
Region 5	0	0	0	28	10	38

For all these regions, the difference between the minimum ($\alpha = 0.5$) and average (α from 0 to 1) values of transported distance is around 20 km. In the region 2, the difference in average is even 27 km per transported t of CW. With α_i equal 0.5, the transport distances are shorter and flows optimal. It has been obvious that some types of waste have to be transported on longer distances from technological reasons, but overall this approach identified the significant potential for efficient traffic management of CW. We assume that the real transport more follows the average value beside the optimal (see Table 1).

5. Conclusion

This article presents methodology approach and benefits in terms of estimating the potential for future planned construction of new processing infrastructure. This tool has been tested through a case study involving the particular stream of combustible waste (network with 206 nodes). The presented results of simulations can be used for prognosis by Justine tool (Zavíralová et al., 2015), including the estimated probability arising from the histogram in the Figure 5b. In this scenario approach, it is necessary to consider existing correlation between regions, which affects each other mostly in the vicinity. The results of calculations can identify potential in terms of transport efficiency and thus significantly contribute to the reduction of GHG emitted during transportation of CW. The key benefit in terms of GHG reduction is a good basis for planning of new projects that are in line with the waste hierarchy. The main objective is to reduce landfilled waste, which produces large quantities of GHGs (CH_4, CO_2, NH_4). The precision of results can be significantly increased by calculating for individual waste codes separately. However, any commodity, which is included in supply chain models can be handled in a similar way. In the further possible extensions of the presented tool are additional criterions, i.e. more specific transport cost, waste treatment cost criterion or influence from stakeholders in decision-making.

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