CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761180

Robust Facility Location Problem for Bio-waste Transportation

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The article presents an optimisation tool for bio-waste facility allocation. The quantity of bio-waste produced in individual territorial units is a key factor for the selection of localities when constructing a new facility. Bio-waste production changes over the course of the year and differs between various types of housing developments. Separation rate is a determining factor for bio-waste production. Readiness to separate the waste reflects the total quantity of bio-waste produced. Predicting the future of bio-waste production is a complex problem, and it would be suitable to consider more developed scenarios. The introduced tool takes into consideration additional possible scenarios for production and provides a robust solution from the point of view of a locality suggestion for the construction of the processing facility. The optimisation model is based on the two-stage stochastic programming approach. The decision regarding the locality for the construction of a new facility is made during the first stage. This method is called the "Here-and-Now" approach. The results are presented in a case study for a selected region in the Czech Republic. Since changes to the legislation in 2014, municipalities are now supposed to provide the possibility to collect the bio-waste of citizens. This has caused significant growth in production – about 20 % annually over the past few years. At this point, it is very complicated to estimate a future trend based on the historical data. Due to this reason, it would be appropriate to consider future bio-waste production across more scenarios. In order to enable the applicability of the tool on a large area with many nodes, it would be necessary to adapt the computation method according to its computational complexity.

1. Introduction

Waste management still falls among the most challenging (e.g., environmental) problems for the growing world. During the last decade, the amount of solid waste has been growing year-by-year due to rapid urbanisation and increasing population growth (Wu et al., 2014). From the total amount of municipal solid waste produced, 40-50 % of it is considered to be a biological waste (Sotiropoulos et al., 2016). Since an obligation on the part of municipalities to enable the separate collection of biodegradable waste (BDW, alternatively biologically degradable communal waste) for citizens was first stipulated in the legislation of the Czech Republic in 2014, the production of this waste has been growing significantly.

The development for the past several years is shown in Figure 1. By reason of intervention in the manner of BDW collection, it is impossible to estimate future production on the basis of historical data. Due to a significant increase in waste production over the past several years, the current trend has an exponential character; this trend is going to change over the years until the final value of production converges towards a value limiting the potential for individual producers (schematic illustration in Figure 1; a potential motivation for future work).

This significant change in waste production provided a sense of urgency for solving a lack of processing infrastructure in the Czech Rep. (Hrabec et al., 2016). BDW can be divided into two types of waste: 1. Public green waste (PGW) – waste produced due to the maintenance of gardens, parklands, and city greenery (grass or flower cuttings and hedge trimmings); 2. Household green waste (HGW) – waste produced by households;

Please cite this article as: Hrabec D., Šomplák R., Nevrlý V., Janošťák F., Rosecký M., Kůdela J., 2017, Robust facility location problem for bio-waste transportation, Chemical Engineering Transactions, 61, 1093-1098 DOI:10.3303/CET1761180

this type is a mix of waste from gardens (mainly grass) and from kitchens (domestic food waste). Following our experiences, the structure of HGW differs significantly according to the type of housing development.

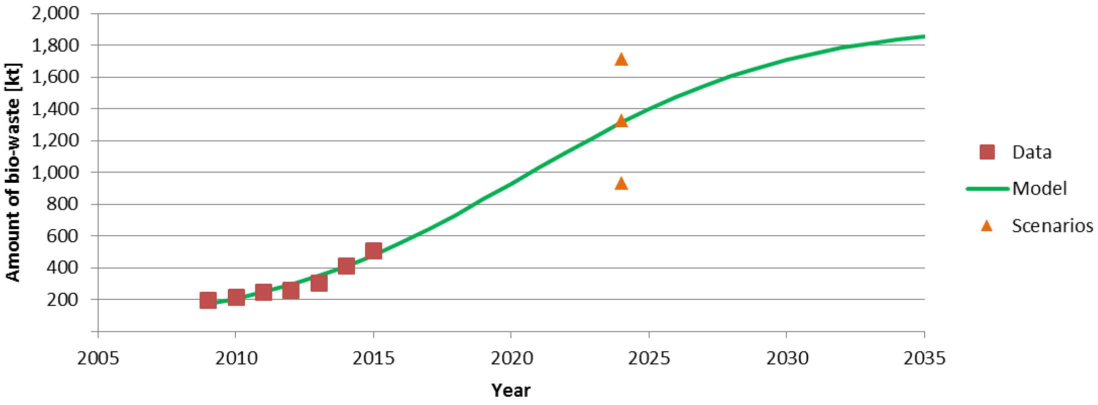

Figure 1: Illustration for the Czech Republic; the limit value, which is based on built-up area and public green vegetation areas, is about 2,000 kt/y; the predictive model is based on an S-shaped curve

In this paper, we develop a mathematical model for the so-called bio-waste transportation problem in order to suggest the best possible locations for potential treatment facilities, i.e., composting plants in our case. According to the available data, the developed model utilises the "Here-and-Now" (HN) scenario-based approach of stochastic programming. Over the last decade, there have been many papers that deal with various similar issues. A literature review on the recent state of work is further presented.

1.1 Literature review

The paper presents a waste management problem that spans several streams of the literature. One of the main streams involves the literature dealing with mathematical modelling in the fields of facility location problems (FLPs), and related waste collection. An extensive review of existing articles in the field of FLP and the potential optimisation of waste collection is provided by Ghiani et al. (2014). A survey on robust optimisation approaches in location problems is provided by Baron et al. (2011). For stochastic FLP see Serrano et al. (2015); see alsolater Hrabec et al. (2016) for the waste management FLP in the Czech Republic. Ferdan et al. (2015) provide a work dealing with the highest risk: the potential lack of waste in relation to the planned capacity. Although Berglund and Kwon (2014) provide a mathematical optimisation model that combines location and routing decisions for hazardous waste facilities under uncertainty, it may also serve as a suitable survey of waste-related optimisation problems with regard to FLPs. Rentizelas et al. (2014) combined municipal solid waste and biomass system optimisation for district energy applications; however, the location decision is made in a continuous space.

Since bio-waste belongs among the most important sources for renewable energy production, the second stream relates to this field (Touš et al., 2011). Lake et al. (2017) reviewed primary energy sources, including the deployment of more and more renewable energy streams. BDW can be processed both at a composting plant and at a bio-gas station. Household waste, which also contains the so-called gastro-waste, has to first be preprocessed (hygienised) before the processing itself starts, bringing with it higher cost.

Nevertheless, most of the recent papers use the so-called "Wait and See" approach while this research utilises the HN approach to the scenario-based stochastic model. In addition, compared to the common HN approach, we implement an analysis of additional forced costs changes in the case of costs parameters changes.

2. Problem definition

In this part of the paper, general approaches for the assessment/determination of input data and the solvability of the optimisation task for BDW treatment are described.

2.1 BDW production

Since the necessary historical data concerning BDW are not available, a production forecast can only hardly be performed. Since there is a need to forecast BDW production considerably, in advance (a new processing infrastructure is planned), this problem can be approached based on an estimate of potential. This potential can be estimated based on the experiences of municipalities, where waste separation has already stabilised and is undertaken at a very high level.

BDW separation highly depends on the type of housing development. It was determined that waste from family homes could be sorted on average in the volume of 150 up to 180 kg/citizen annually. The potential of BDW

separation is significantly lower for residential housing developments and blocks of flats. This was determined to be from 60 up to 80 kg/citizen annually.
Waste production from the public greenery varies depending on the size of the individual areas. Waste production can be estimated within the range of 5 up to 20 t/ha. The highest recovery ratio comes from playgrounds. On the contrary, a low recovery ratio was recorded for fencing, beaches, and parkways. Since future waste production is unknown, it is necessary to take a stochastic approach. This paper focuses on the HN approach, where a number of possible scenarios for future development is considered (see Figure 1).

2.2 Transportation cost

Unit costs associated with the transportation of waste are very often considered to be constant for the entire transportation infrastructure within the optimisation tasks. But the transportation costs are in fact highly dependent on the ratio of time spent for manipulation and transportation. Another significant factor is reduced working hours, which can lead to the extension of a car fleet. When BDW is concerned, we must fix the collection time and then disposal time to the place of processing, including all manipulations. For this reason, an adequate description of the transportation network has to be applied. We need to have information about a producer and at what facility the waste was processed (Šomplák et al., 2015). A network, which interconnects each producer with each potential processor, facilitates this process.

2.3 Processing cost

Costs associated with BDW processing can be divided according to the waste structure and type of facility. The price is fixed from a valid price list for operated facilities, and a possible price alteration can be considered both over time and within a certain time interval. There is a different situation for potential projects where the capacity is unknown, and so the price of processing is unknown. The price of processing is highly variable together with changes in the capacity; see Figure 2 that shows the proportions of the dependency of overall costs on the processed volume. The concave function at the minimisation of costs often results in difficulties with finding a global extreme. This problem can be solved through the linearisation of the application with parts of the continuous linear function. Possible inaccuracies that may occur are shown in Figure 2 (the right part).

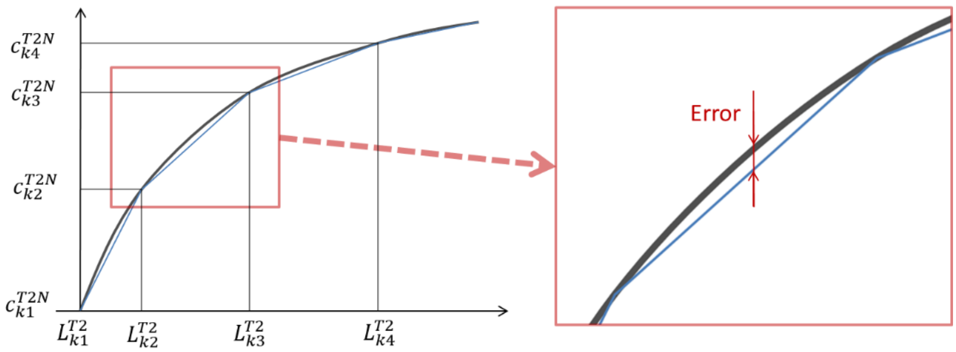

Figure 2: Schematic illustration of the linearisation of price functions

The linearisation mentioned uses the so-called SOS2 variable, which ensures that the independent variable L_{kb}^{T2} (where $b = 1, 2, 3, 4$) switches between individual intervals $(L_{k1}^{T2}, L_{k2}^{T2})$ up to $(L_{k3}^{T2}, L_{k4}^{T2})$. This is provided by the character of SOS2 variables, for which two non-zero adjacent elements can be applied as the maximum.
This effect occurs for BDW processing mainly when HGW is processed due to the necessary preprocessing. These facilities can process also PGW, where preprocessing is not required, and costs, kept in a relatively constant mode, can be considered (or possibly within a certain time interval) independent of capacity.

2.4 Mathematical model

Using notation from Table 1, we develop the mathematical model, which consists of an objective function Eq(1), that minimises the total cost of transportation and treatment for both types of waste, and constraints Eq(2) - Eq(7):

$$\min \sum_{s \in S} p_s \left(\sum_{j \in J} x_{js}^{T1} d_j e_j^{T1} + \sum_{j \in J} x_{js}^{T2} d_j e_j^{T2} + \sum_{i \in I} \sum_{j \in J} A_{ij} x_{js}^{T1} c_i^{T1E} + \sum_{i \in I} \sum_{j \in J} A_{ij} x_{js}^{T2} c_i^{T2E} + \sum_{k \in K} \sum_{j \in J} A_{kj} x_{js}^{T1} c_k^{T1N} + \sum_{k \in K} \sum_{b \in B} f_{kb} c_{kb}^{T2N} \right). \quad (1)$$

Table 1: Mathematical model related notation

Type	$Symbol$	Description
Sets	$h \in H$	vertices (producents of waste and treatment facilities)
	$i \in I \subset H$	vertices of existing treatment facilities
	$k \in K \subset H$	vertices of potential treatment facilities
	$j \in J$	transportation arcs/edges
	$b \in B$	auxiliary index for linearisation of cost functions
	$s \in S$	set of scenarios
Parameters	A_{hj}	incidence matrix
	d_j	transportation distances
	e_j^{T1}, e_j^{T2}	transportation cost for PGW and HGW
	c_i^{T1E}, c_i^{T2E}	processing cost of PGW and HGW in existing treatment facilities
	c_k^{T1N}, c_{kb}^{T2N}	processing cost of PGW and HGW in potential treatment facilities
	w_h^{T1}, w_h^{T2}	PGW and HGW production
	C_h^{T2}, C_h^{total}	maximal capacity for processing of HGW and all waste
	L_{kb}^{T2}	maximal capacity for processing of HGW in potential treatment facilities
	p_s	the probability of scenario s
Variables	$x_{js}^{T1},\ x_{js}^{T2}$	the amount of transported PGW and HGW
	f_{kb}	auxiliary variable for linearization of cost functions – SOS2 variable

The first and second component of objective function Eq(1) express the transportation costs for the considered types of BDW. The third and fourth elements specify the processing cost for the considered types of BDW in existing treatment facilities. These facilities are in operation and their capacity and processing costs are already given. Reconstruction is not considered in these projects. The last two components relate to costs of the newly built facilities. Moreover, the described optimisation task must respect following constraints:

$$\sum_{j \in J} A_{hj} x_{js}^{T2} + w_h^{T2} \leq C_h^{T2} \qquad \forall h \in H, \forall s \in S \qquad (2)$$

$$\sum_{j \in J} A_{hj} \left(x_{js}^{T1} + x_{js}^{T2} \right) + w_h^{T1} + w_h^{T2} \leq C_h^{total} \qquad \forall h \in H, \forall s \in S \qquad (3)$$

$$\sum_{j \in J} A_{kj} (x_{js}^{T1} + x_{js}^{T2}) \leq \sum_{b \in B} f_{kb} L_{kb}^{T2} \qquad \forall k \in K, \forall s \in S \qquad (4)$$

$$\sum_{b \in B} f_{kb} = 1 \qquad \forall k \in K \qquad (5)$$

$$x_{js}^{T1}, x_{js}^{T2} \geq 0 \qquad \forall j \in J, \forall s \in S \qquad (6)$$

$$f_{kb} \in \langle 0,1 \rangle \qquad \forall k \in K, \forall b \in B. \qquad (7)$$

Constraint Eq(2) limits the amount of processed household waste. It is substantial for treatment facilities that cannot process household waste for technological reasons. Constraint Eq(3) restricts the total processed amount of waste. Constraint Eq(4) links the cost with the processed amount of household waste in new facilities by variable f_{kb}, which is of an SOS2 type (see Figure 2). Eq(5) ensures that linearisation of the cost function has the required parameters, while constraints Eq(6) and Eq(7) state the domains of the variables.

3. Case study – a particular region locality in the Czech Republic

Herein, a region of the Czech Republic in which two facilities for waste processing are already located (one cheaper 30 km away from the considered city and one more expensive 15 km away) is considered. Moreover, for the city under consideration, there are six possible locations for a new facility (composting plant). The cost for waste processing is considered the same for all locations in the principle from Figure 2. Then, the way of acquiring input data should be determined. This consists of the division of the particular territory into smaller areas, which will be represented with one point (node of the flow task). There were 10 such areas determined. Furthermore, a transportation network should be established based on real infrastructure. Production for an addressed year is determined within each node for three possible scenarios. Further suitable locations for the possible development of new processing facilities have to be selected. The last input is price parameter for the transportation and processing of individual types of waste (from the PGW).

The task under investigation is conceived until 2024 (prohibition on storing of usable waste in the Czech Republic). With respect to the significant amount of time, there is an assumption that the level of separation of bio-waste will grow significantly (it has already shown on average an increase of 20 % annually for the last 3 years). It can be expected that the waste production in many municipalities will be approaching the limit values (see above) in the year 2024. Waste production at the levels of 50 % (SC1), 70 % (SC2), and 90 % (SC3) of the limit value for the given territorial unit was considered for the subsequent calculation (see Figure 1).

Table 2 shows a comparison of the objective function value (OFV) for each scenario, where "Existing/New" means whether the responsible person decides to use an existing facility or build a new one (with optimal capacity). Clearly, if New<Existing, it is better to build a new facility. For HN, there is a comparison of the different capacities of the new facility (composting plant). ES is different for the OFV of a building facility with a given capacity and the use of an existing facility. MPE (Maximum price expenditures) shows the OFV for the highest possible price of an (existing) cheaper facility (the possibility of cartel occurrence is not considered here); the highest possible price means the limit value until it is no longer advantageous to use other alternative solutions. It also demonstrates that if the region does not have its own facility, it becomes (up to some point) dependent on the arbitrariness of the existing facility owners. EG (Expenditure gap) is different for HN (i.e., current price) and MPE. SR expresses how much a municipality can save against MPE if it decides to build a new facility. Finally, SRESR describes how many times SR is greater than ES, i.e., the greater the SRESR the better the solution for the municipality.

Table 2: Expenditures for each scenario (SC); amounts in EUR

	Expenditures		Capacity of new facility (t/y)				
	Existing	New	1,000	2,000	2,500	3,000	4,000
SC1	77,546	79,088	-	-	-	-	-
SC2	102,659	102,391	-	-	-	-	-
SC3	127,771	79,088	-	-	-	-	-
HN	102,659	-	104,348	103,519	103,401	104,108	110,708
ES	-	-	1,690	861	742	1,449	8,049
MPE	131,211	-	123,735	113,752	110,333	108,003	111,201
EG	28,553	-	19,387	10,233	6,932	3,896	494
SR	-	-	9,166	18,319	21,621	24,657	28,059
SRESR [-]	-	-	5.4	21.3	29.1	17.0	3.5

ES – Extra surcharge, MPE – Maximum price expenditures, EG – Expenditure gap, SR - Saved risk, SRESR – SR to ES ratio

Figure 3a and 3b is a graphical representation of ES and SR (SRESR) from Table 2. It can be observed that the optimal trade-off is to build a new facility with a capacity of 2,550 kt/y.

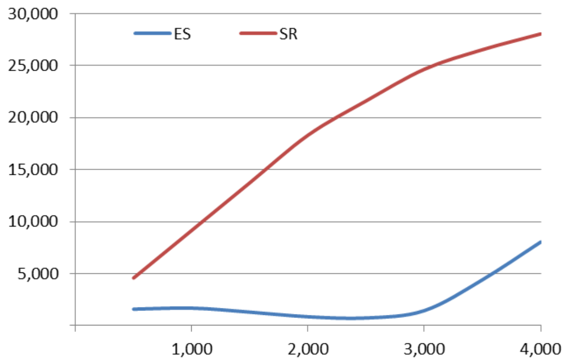

Figure 3a: Saving/expenditure against capacity

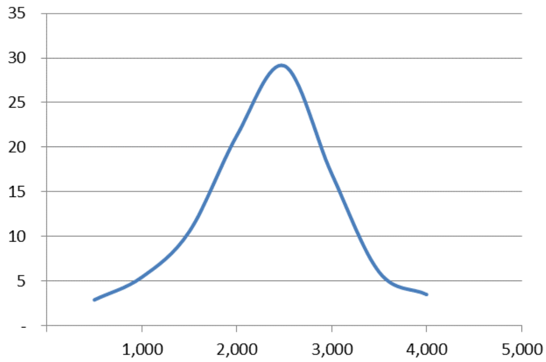

Figure 3b: SRESR against capacity

4. Conclusions and further research

This paper has introduced the benefits of stochastic programming for the case of making decisions on the construction of bio-waste processing infrastructure. Future bio-waste production is the main unknown in this task. The possible maximum values have been discussed herein; however, how actual production can reach these limit values is not clear. This approach has been demonstrated through a case study in the Czech Republic, where the basic task based on the “Here-and-Now” approach was extended with a risk analysis of additional cost due to changing market conditions. The development of the market environment can be, in general, hard to predict and its implementation into the basic task is not often possible. An indicator which describes the reduction of risk through an increase in processing cost has been defined in this paper. This indicator provides significant support for the investment decision-making process.

An interesting question arises with the following situation. Let a solution with only existing facilities is better than a solution considering a new facility (see solutions for SC2 and SC3 as well as for HN case in Table 2). In such cases, an optimal decision is to utilise only existing facilities but then, the region is dependent on facilities that are not controlled (in the sense of processing cost). What if the processing cost in the existing facilities will become more expensive in the (near) future? Would the solution still be advantageous from a municipality perspective? Alternatively, when the worst solution can be accepted? An analysis of similar risk situations is referred as one of our future research directions.

Acknowledgments

The authors gratefully acknowledge financial support provided by the MEYS under the National Sustainability Programme I (Project LO1202) and financial support provided by Technology Agency of the Czech Republic within the research project no. TE02000236 ”Waste-to-Energy (WtE) Competence Centre”.

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