Mikkola, Susanna; Harjunkoski, Iiro; Jämsä-Jounela, Sirkka-Liisa

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Published in:
Automaatiopäivät22

Published: 22/03/2017

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Mikkola, S., Harjunkoski, I., & Jämsä-Jounela, S-L. (2017). Optimization scenarios for Waste-to-Energy systems. In *Automaatiopäivät22* (Automaatiopäivät22 Proceedings). Suomen Automaatioseura.

Optimization scenarios for waste-to-energy systems

Susanna Mikkola
Aalto University School of Chemical Technology, Kemistintie 1, 02150 Espoo, Finland.
E-mail: susanna.s.mikkola@aalto.fi

Iiro Harjunkoski
Aalto University School of Chemical Technology, Kemistintie 1, 02150 Espoo, Finland.
iiro.harjunkoski@aalto.fi

Sirkka-Liisa Jämsä-Jounela
Aalto University School of Chemical Technology, Kemistintie 1, 02150 Espoo, Finland.
sirkka-liisa.jamsa-jounela@aalto.fi

KEY WORDS Optimization, supply chain, waste-to-energy (WTE), municipal solid waste (MSW)

ABSTRACT

A generic municipal solid waste management (MSWM) supply chain model was developed, using mixed integer linear programming (MILP). The model consists of waste collection, separation, processing and product delivery parts. Data from a Mexican case study on waste management of Santibañes-Aguilar et.al. was applied for starting point for the model development. The Mexican case study was a single period optimization of the supply chain framework.

The generic model does not represent any existing municipal solid waste (MSW) chain. The structure of the model was adopted from a Mexican case study, however, in a modified form in order to make it more relevant to Nordic countries. Testing the model was performed in parts. This means that the model is tested and showed that the results are valid when the new part of the supply chain is added to the model. The testing showed the model reacts logically to changes in the input data.

The model was built in general algebraic modelling system (GAMS) program, which applies MILP. It's formulation includes several mass balances, constraints for transportation and processing and objective functions. The constraints involve the different phases of the MSWM supply chain such as separation, final disposal, the distribution of products, the transportation of waste and processing of waste to acquire value-added products. The optimization model can simultaneously select the processing facilities and technologies for the MSW collected from the different sites and the distribution of wastes to dumps, plants and markets. The cost functions relate to minimizing the costs and maximizing the profit. Present model could be modified for additionally maximizing MSW reuse. This would require of using multi-target optimization.

1 INTRODUCTION

Digitalization, urbanization and population growth along with finite natural resources are examples of megatrends shaping the world. These trends affect the long-term viability of megacities. While economy is growing environmental and social impacts need to be monitored. Energy and waste are important elements in megacities management. Energy consumption is growing and greenhouse gases (GHG) emissions are increasing. Municipal and industrial wastes are both generated in the megacities at a high rate. For this reason, it is important to dispose waste harmlessly in order to build resource savings and an environmentally friendly society, as well as to reduce pollution and to improve living environment.

Available landfill space and natural resources are diminishing while the energy demand is growing. An urgent need for renewable energy utilization is in high-rise as a result of a growing international market and ambitious goals for increased material recycling. Therefore, waste management is required mainly to avoid pollution and high landfill demand. In order to reduce simultaneously waste volume and produce energy in cities waste-to-energy (WTE) solution is presented. The waste type utilized by the WTE system is limited to MSW in this work.

MSWM supply chain consists of household collection, treatment, material recycling, compost, waste disposal and transportation. Because the disposal of MSW in landfills is not enough, the WTE processing plants are introduced to the MSWM supply chain. As a result, the adjusted supply chain includes collection, pre-treatment, storage, transport and energy conversion. Optimization is required for the short-term production planning (scheduling). Typically, scheduling problems include allocating resources and time slots, constraints and optimization. Ensuring that resources are timely available requires the exact planning of equipment, material, utilities and personnel. Scheduling problems relate to every phase of the MSWM supply chain. Optimizing the whole supply chain results in both economic and environmental benefits.

2 GENERIC WASTE MANAGEMENT MODEL

The target was to develop a generic MSWM supply chain model. The generic model consists of waste collection, separation, processing and product delivery part. Data from the Mexican case was applied for testing and demonstration (Santibañez-Aguilar, Martinez-Gomez et al. 2015). Significant part of the Mexican model features, parameters and variables are pieced together to the generic model. The Mexican model is very complex. It was modified from 2013 to 2015 by adding social risk and including sites within the cities (Santibañez-Aguilar, Martinez-Gomez et al. 2015, Santibañez-Aguilar, Ponce-Ortega et al. 2013). The social risk formulates form total fatalities such as fatalities form intoxication and leaching. It is not considered as a big problem in Nordic countries environment. Therefore, social risk is excluded from the generic model and a more simplified model of the Mexican case is modelled with only part of the indexes included. The present model covers all parts of the MSWM supply chain model, see **Figure *1***. However, the indexes were limited to those considered representing a typical MSWM supply chain in Nordic countries.

The indexes included in the present model include:

- d = index used for dumps
- s = index that represent the sites in the cities

- wt = index for the considered waste in the supply chain
- pf = index for processing facilities for waste processing
- tech = index used for waste processing technologies
- p = index used for products

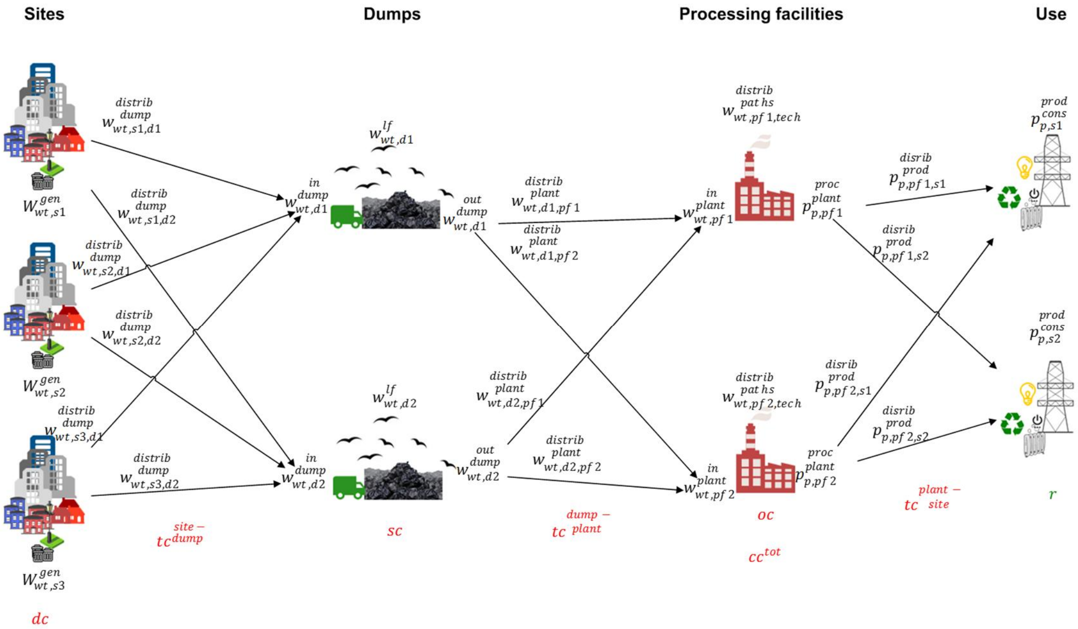

Figure 1. Entire MSWM supply chain.

2.1 Collection part

The collection part models a situation where MSW is generated at sites with a specified rates for different waste types. The waste is collected and distributed to different dumps where part of the waste is disposed and part is sent for processing. The costs associated to the collection part include transportation cost from site to dump and waste disposal cost. There are no constraints in the collection part. However, landfill capacity could be considered as a constraint. It would be useful especially if the examined period would be long. The optimization target aims at minimizing the transportation costs associated to the collection part. There is no revenue associated to this part of the model.

2.2 Waste separation part

Waste separation part models MSW separation from the waste inlet flow to dumps ($w_{wt,d}^{\substack{in\\dump}}$). The amount of waste that cannot be separated is left to the dumps. The separated MSW amount ($w_{wt,d}^{\substack{out\\dump}}$) is based on a waste type specific separation factor ($\alpha_{wt,d}^{sep}$), Equation 1. The additional costs associated to the separation part include transportation cost from dumps to facilities and waste separation cost. The objective function in this part could aim at maximizing the separated waste. However, the separation factor limits the out flow of the waste. The present model focuses on cost minimization as target. Clearly maximizing the MSW reuse would be an important target from environmental point.

$$w_{wt,d}^{\overset{out}{dump}} \leq \alpha_{wt,d}^{sep} * w_{wt,d}^{\overset{in}{dump}}, \forall wt \in WASTE, d \in DUMPS \quad (1)$$

2.3 Waste processing part

Waste processing part considers processing of separated waste with different technologies to the various value added products. The present model has the same set of technologies at all processing facilities following the Mexican model. Different waste types can be processed with different technologies. The waste is distributed to technologies ($w_{wt,pf,tech}^{\overset{distrib}{paths}}$) to generate different products ($p_{p,pf}^{\overset{proc}{plant}}$) with the predetermined production (conversion) factor ($\alpha_{wt,p,tech}^{conv}$).

$$p_{p,pf}^{\overset{proc}{plant}} = \sum_{tech \in PATHS} \sum_{wt \in WASTE} \alpha_{wt,p,tech}^{conv} * w_{wt,pf,tech}^{\overset{distrib}{paths}}, \forall p \in PRODUCTS, pf \in FACILITIES \quad (2)$$

The Mexican model does not have capacity data for the processing facilities. Unlimited processing capacity is not realistic. Therefore, in the present model capacity limits for processing plants are added. A binary variable ($y_{wt,pf}$) for the processing facility capacity is added to the model. With the help of the binary variable the model steers the distribution of waste to plants ($w_{wt,d,pf}^{\overset{distrib}{plant}}$) towards the upper limit ($W_{wt,pf}^{\overset{proc}{up}}$), which is more profitable or productive and limits the disadvantageous plants use to zero.

The plant capacity limits for processing waste are multiplied with the binary variable, see Equations 3 and 4. As a result, the model uses a nonzero threshold value for processing. If the binary variable is zero, both lower ($W_{wt,pf}^{\overset{proc}{lo}}$) and upper limits are zero and nothing is processed in the plant. Otherwise, the amount of processed waste in the plant is at least the amount of the lower limit and below the upper limit or between the upper and lower limits.

$$\sum_{d \in DUMPS} w_{wt,d,pf}^{\overset{distrib}{plant}} \geq W_{wt,pf}^{\overset{proc}{lo}} * y_{wt,pf}, \forall wt \in WASTE, pf \in FACILITIES \quad (3)$$

$$\sum_{d \in DUMPS} w_{wt,d,pf}^{\overset{distrib}{plant}} \leq W_{wt,pf}^{\overset{proc}{up}} * y_{wt,pf}, \forall wt \in WASTE, pf \in FACILITIES \quad (4)$$

For the model testing the capacity limits are set such that the total processing capacity for each waste type correspond to a capacity buffer amount of the potentially available processed waste. The capacity buffers varied between 20% to 100% excess processing capacity. This means that in the model the available processing capacity does not limit the production. On the contrary, the number of plants/technologies could be reduced and the model identifies which plants are least important in the MSWM supply chain.

The costs associated to the processing part include operating cost and total capital cost. There are no additional raw material costs. The capital cost is annualized with the annualization factor. The investment cost are paid in 20 years.

2.4 Product delivery part

Product delivery part models just the selling of the products to customers. The markets at sites have demand limits for the products. In the Mexican model, products sent to consumers needed to be lesser or equal than the demand. In the present model, there is lower limit for the demand. The lower limit forces the model to produce at least the lower amount. The costs consist of transportation cost to consumers and profit is achieved from revenue from sales. Revenue (r) from sales equals the sum of unit price of product ($\overset{unit}{C_p^{prod}}$) multiplied by the total amount of products sent to market ($\overset{prod}{p_{p,s}^{cons}}$), see Equation 5.

$$r = \sum_{p \in PRODUCTS} \sum_{s \in SITES} \overset{unit}{C_p^{prod}} * \overset{prod}{p_{p,s}^{cons}} \tag{5}$$

2.5 Cost functions and optimization targets

The optimization targets focus mainly on economic objectives. Present model can be used for documenting the effectiveness on MSW reuse. The model could also be used for maximizing MSW reuse as a single objective. It would, however, be more realistic to use multi-target optimization with cost minimization and MSW reuse maximization as targets. The optimization target of the entire supply chain is to maximize the net annual profit see Equation 6. The total profit formulates from revenue minus the costs included in the entire supply chain like operation cost (oc), capital cost (cc^{tot}), total transportation cost (tc^{tot}), disposal cost (dc) and separation cost (sc).

$$f = r - oc - cc^{tot} - tc^{tot} - dc - sc \tag{6}$$

where the total transportation cost for the supply chain is

$$tc^{tot} = tc^{\overset{site-}{dump}} + tc^{\overset{dump-}{plant}} + tc^{\overset{plant-}{site}} \tag{7}$$

3 ANALYSIS RESULT

Analysis results show that some waste types are processed to the maximum possible. The rest of the waste types are processed only to satisfy the market lower demand limit. The waste processing is profitable only for a few products with the Mexican case study data, see **Table *1***. In the table, waste processing costs are calculated per ton.

The profitability calculation table shows if it is more profitable to dispose waste or process it. The unit disposal, separation, processing and variable cost are acquired from the Mexican case study. The calculation does not consider fixed cost or transportation costs. Profit from processed waste is calculated subtracting separation, processing and variable costs form revenue. Waste processing becomes profitable when profit in exceeds the disposal cost. The profitability calculation explains why only a few waste types are processed. For the other waste types, it is more profitable or less costly to dispose than it is to process them. In the Mexican case study the disposal cost is very low compared to for example separation cost. The reprocessing settles to the separation factors maximum amount when the processing facilities have unlimited capacities. In the product delivery model the lower demand of products in the markets forces the model to generate other products, even if they are unprofitable according to the **Table *1***.

Table 1. Profitability calculation.

Waste processing, cost ($US/ton)						
	Disposal	Profit	Separation	Processing	Variable	Revenue
PP	-12	32809	235	2604	52	35700
PE	-12	19509	235	2604	52	22400
PET	-12	16109	235	2604	52	19000
PS	-12	-383	235	388	5	245
HDPE	-12	-363	235	206	3	80
Aluminium	-12	974	235	90	1	1300
Clear Glass	-12	-206	235	10	0.3	39
Green Glass	-12	-206	235	10	0.3	39
Brown Glass	-12	-206	235	10	0.3	39
Paper	-12	-63	235	4	0.4	177
Nonrecyclables (Mixture)	-12	-124	235	40	4	155

The optimization of the MSWM supply chain occurs in a relation to the transportation costs. Transportation cost minimization determines the distribution of production between plants. The objective was to maximize the net annual profit. Unit cost for disposal and separation are same for every waste type. Optimizing disposal cost means that the more waste should be separated, which would lead to decreasing the total disposal cost. The separation cost is the dominating factor in the Mexican case study see **Table *1***. Processing cost depends on the waste type and which technology is used. Variable cost depends on the technology and fixed cost is constant. The model optimizes the processing and capital costs by choosing the most optimal combo. Therefore, not all the technologies are used only the most profitable ones with lowest variable cost and high conversion factor relation. Revenue is made from selling the products. The model optimizes the production in such a way that the revenue is at maximum. The conversion factor and the prices of products affect the revenue.

4 CONCLUSION

A generic MSWM supply chain model was developed basing on the Mexican case study data. The MSWM supply chain model minimizes costs associated to the MSW treatment and maximizes the net annual profit. The model can detect excess process capacity and it can be used for the MSWM supply chains optimization.

The analysis results show that the waste processing is only partially profitable when the Mexican case study cost structure is used. The disposal cost is insignificant compared to the separation cost and for this reason the end product price must be substantial before the production becomes profitable. In order to reach maximal reuse of all MSW types the disposal cost should be substantially increased.

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