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Mixing Approach to Waste Composition and its Lower Heating Value Impact on Waste-to-Energy Plant

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Recent research on waste management has primarily focused on the circular economy. This concept leads to increased sustainability by putting emphasis mainly on the reduction of waste production, recycling, and restriction of landfilling. It has already been incorporated in many national directives and legislations, while its effective implementation can be aided by mathematical programming. For the optimal operation of Waste-to-Energy plants, it is necessary to take into consideration the varying compositions and lower heating values (LHV) of the utilized wastes (or other commodities suitable for energy recovery). Because the LHV significantly influences the plant operating mode, waste heterogeneity can result in serious operating problems if bad strategic decisions had been made. The approach discussed represents a mixing task which considers the heterogeneity of wastes originating from different sources, the corresponding LHVs, and their impact on the final energy recovery. The implementation includes plant locations and network flows, operating costs (together with the return on investment), waste transport, and corrections of LHVs because all these factors are closely linked to the resulting profits from energy sales. The constraints consist of the necessary balances, such as capacities or heating limits. The developed optimization model is verified using a small waste transport network. The result of the model is a proposal for the redistribution of the mixed municipal waste, bulky waste and other combustible waste into specific technology sinks (Waste-to-Energy plant, landfill, cement plant). This article focuses on energy recovery from waste, which is also a crucial part of the transition to the circular economy. Future research is also outlined concerning the extension of the model's environmental component and the large size of typical, real world optimization tasks of the respective type.

1. Introduction

Utilization of waste as a source of energy nowadays is an integral part of efficient waste management based on the principles of the circular economy (Ng et al., 2014). This waste disposal method is generally known as Waste-to-Energy (WtE). The primary function of WtE lies in energy recovery from the residual fractions of municipal solid waste (MSW) and the return flows of materially non-utilizable wastes with energy potential, which would otherwise have to be landfilled (Giugliano et al., 2008). The composition and amount of generated MSW depend on the level of economic development, cultural norms, geographical location, energy sources, and climate (The World Bank, 2012). As stated by Ziegler-Rodriguez et al. (2018), MSW consists mainly of bio-waste, paper, plastics, glass, metals, and other components and the distribution of the individual fractions varies significantly. Some articles analyze the thermochemical properties of the waste components with respect to their energy utilization (Zhou et al., 2015). Nowadays, it is desirable to separate some of the fractions for further recycling. However, the residual mixed municipal waste (MMW), in case of which the separation of materially utilizable fractions is very difficult and inefficient (Zhuang et al., 2008), constitutes the major part of MSW. MMW is more often used for energy recovery. The studies dealing with WtE have discussed various optimization strategies regarding MSW processing and the related location (Hu et al., 2017) or network flow (Bing et al., 2014) problems. These approaches do not consider the compositions of wastes coming in from different localities. At the same time, there exist more types of waste suitable for energy utilization. These primarily

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include selected fractions of bulky waste (Šomplák et al., 2019) and combustible industrial wastes whose efficient material recovery is not possible (Garcés et al., 2016).

Effective waste management is related to the sustainability of the industry in relation to the environment. In the case of WtE, it is appropriate to consider the combined production of heat and electricity. For this concept to be effective, it is necessary to include the heterogeneity of the input waste. According to a recent review of methods supporting sustainable supply chain decisions (Barbosa-Póvoa et al., 2018), available studies consider neither the heterogeneity nor its link to the operating conditions of WtE plants. In general, the mixed waste can have a variable lower heating value (LHV). The paper by Ferdan et al. (2015) shows that energy production is a significant income for a WtE plant and it is appropriate to consider optimisation of the production from the perspective of input waste. Waste heterogeneity can pose major challenges to WtE operation and represents an important factor to be considered in the design of a facility (Shi et al., 2016). The economic point of view is crucial here because variable LHV of the processed waste can influence the gate fee (Touš et al., 2014). These papers deal only with local studies and assess the impact of waste heterogeneity on facility sustainability. The aim of the present paper is to include this important aspect in a larger scale network flow task and to optimise the waste management process, including energy production, in terms of input material.

This paper presents a Mixed-Integer Linear Programming (MILP) model of a flow network combined with a mixing task for multiple fractions. The aim is to extend the existing models focusing on location and network flow problems in the field of waste management. Such a novel approach considers not only waste transportation and processing costs, but also the operation of WtE plants themselves in the context of local conditions. The main feature of the mixing task is the inclusion of different types of waste streams, which are suitable for energy utilization, with variable thermochemical properties. The combusted mixture then directly influences the operation of the WtE plant. The dependences of each element of the process are analyzed in Section 2 and the data obtained are used as inputs in the MILP model described in Section 3. Subsequently, Section 4 discusses a test case. The overall results are presented in the Conclusions, together with the outline of future development of the presented approach, where the aim is to carry out a case study involving real-world data.

2. Technology and waste flows

The LHV of input waste is given by its composition. The considered fractions of MSW are MMW with 7–11 GJ/t (Doležalová et al., 2013), bulky waste featuring 16–24 GJ/t (Garcés et al., 2016), and other combustible wastes with high LHV – generally 22–30 GJ/t (Garcés et al., 2016). With respect to the listed ranges, the resulting mixture entering the processing plant has an a priori unknown and variable LHV. Figure 1a shows a grate incinerator performance diagram, i.e., a dependence of the total generated heat on the amount of waste being combusted. The highlighted feasible heat production area is bounded by the sloped lines representing the extreme LHVs. The ideal LHV is then given by the line intersecting the reference point R (the conditions for which the incinerator has been designed). This point is linked to the required heat power and is a compromise between LHV and the amount of waste being combusted. Generally, WtE plants are operated under such conditions if possible. An example of the monthly heat demands of a city with approx. 100,000 inhabitants is shown in Figure 1b.

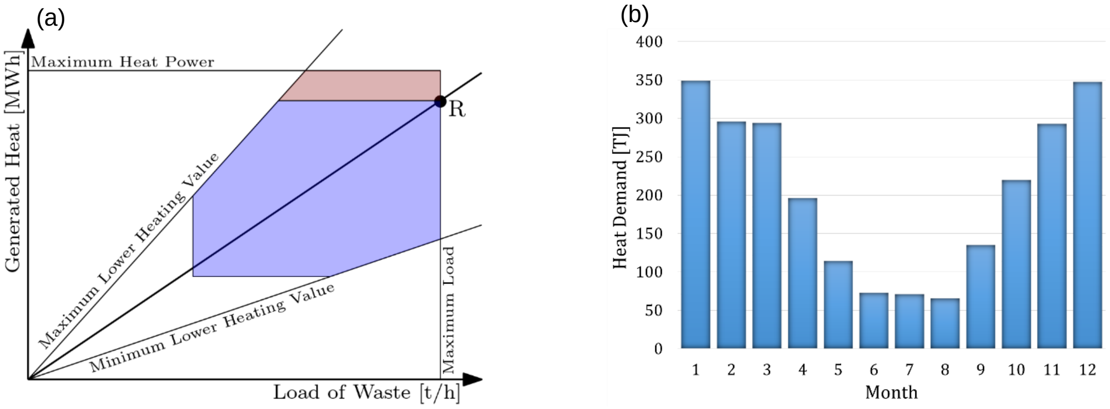

Figure 1: (a) Heat generated in a grate incinerator and (b) Monthly heat demands of a typical city with 100,000 inhabitants

The lower, blue portion of the feasible heat production area in Figure 1a represents operating conditions leading to a state below the reference point. This usually is caused by a lower-than-reference LHV of the incoming waste and results in heat production below the planned value. The actual profit from heat and electricity sales is then also lower. The upper, red portion designates operating conditions leading to a higher production. Its extent is limited and, if LHV is high, the rate at which the waste is combusted must be decreased, causing a decrease in profit from waste processing. The remaining portion of the diagram represents infeasible conditions because either the grate is overcharged or its temperature is too high or too low for proper combustion.

Such influence of LHV can be introduced into the model via a correction function. For the sake of simplicity, a single function reflecting heat demand from Figure 1b was used for all plants and localities. The heat demand is fulfilled as best as possible, and then all excess heat power is transformed to electricity. Production efficiency and energy prices were subsequently factored in to obtain a correction function for each month (Figure 2a), which form an overall yearly balance. The origin represents the reference point. This correction function also depends on the plant processing capacity and cannot cover all plants because the construction of new plants of unknown capacities may be considered. To overcome this limitation, a model covering several representative plants with various capacities was created and then the obtained functions were averaged (see Figure 2b).

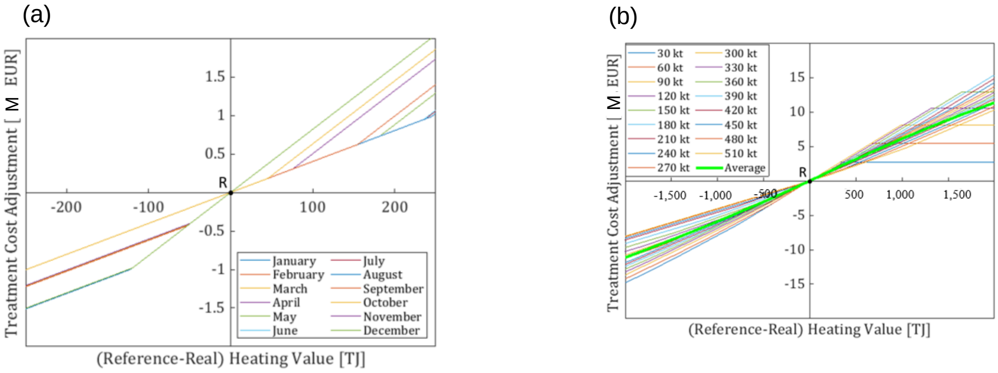

Figure 2: Adjustment cost of waste treatment (a) for individual months and (b) year-round obtained for various plant capacity

A major portion of a WtE plant revenue comes from heat and electricity sales and processing fees (Ferdan et al., 2014). The main expenses include salaries, the necessary chemicals which must be purchased, and fees linked to the disposal of residues. All these are directly proportional to the processing capacity. Existing WtE plants often have the treatment cost per t of waste fixed to a value reflecting economic sustainability. In a case of prospective plants, also the investment cost and its rate of return must be considered. The final gate fee is then – after taking into account all the mentioned factors – a nonlinear function depending on the selected processing capacity (Šomplák et al., 2014).

3. Mathematical model

The model produces a compromise between the investor's revenue and the producer's expense for waste processing. It includes the variable LHV of the waste, transportation cost, and treatment cost so that optimum processing chain is ensured. This constitutes a transportation problem built upon a bipartite graph containing both the producers and the processing facilities. The model considers multiple plant and waste types and assumes that only certain types of waste can be processed in certain types of plants. The existing processing plants in the network can have a predefined capacity. New WtE plants can also be suggested by the model. In this case, the model decides on not only their locations but also their optimum capacities. Investment costs are included in the respective treatment costs which, in turn, ensure the required rate of return. Some functions are linearized using the ordered sets of type 2 (SOS2) variables to obtain an MILP model.

3.1 Objective function

The objective function is given by Eq(1) and minimizes the total cost for waste producers (please refer to the Nomenclature for the meanings of the sets etc.). The first term represents the treatment cost in existing plants, while the second term expresses transportation cost. The third term determines the treatment cost in prospective plants and the correction of revenues from heat and electricity sales. To reach the optimum energy production, the waste mixture delivered to a facility must be of a certain reference LHV. If the actual LHV is different, the net produced heat and electricity will differ from the planned amounts, and the profits from energy sales will not be as expected. The last term then includes into the model the penalization for not meeting the capacities of the existing plants because of high LHV of the waste mixture. This must be multiplied by the treatment cost to ensure the economic sustainability of the plants.

3.2 Constraints

The set of feasible solutions is constrained by the balance equation accounting for the processing capacities of individual plants and transport capacities along the routes from waste producers. Additional constraints govern the lower and higher limits on the waste mixture LHV and inequations limiting heat production according to the design parameters of the incinerators. Another constraint determines the degree to which the requirements on the produced amount of steam are met. This is the difference between the amount of heat which could be produced if the LHV of the mixture was equal to the reference value and the actual amount of heat produced. In the case of prospective plants, the model takes the total amount of processed waste as a dot product of the SOS2 variable and the capacities determined to function approximation. In this way, it is possible to obtain the final treatment cost in such plants. The last few constraints govern the non-negativity of certain variables and normalization of the SOS2 variables.

$$\min\left(\sum_{e\in E}\sum_{e\in E} A_{e,i}x_e \mathrm{P}_i^{treat} + \sum_{e\in E} x_e D_e P^{trans} + \sum_{i\in I}\sum_{k\in K}(\mu_{i,k}^{pro}P_{i,k}^{pro} + \mu_{i,k}^{pen}P_k^{pen}) + \sum_{i\in I_V\setminus I_P} P_i^{treat}(C_i - \sum_{e\in E} A_{e,i}x_e)\right) \quad (1)$$

4. Simple example

The test model considers three types of waste – MMW, bulky waste, and other combustible waste – and the same number of facility types – WtE plant, landfill, and cement mill. To make matters easier, LHVs are taken in this example as the means of the intervals mentioned in Section 2. The resulting processing options are as follows: (a) any type of waste can be landfilled or processed in the WtE plant; (b) cement mills only accept other combustible waste containing fractions with a high LHV. The transportation network consists of 8 nodes and 13 edges with the distances being as indicated in Figure 3. A black square with a number indicates that in the corresponding node there is an existing facility producing or processing the respective type of waste at the given rate (see the legend provided in the figure). Similarly, a gray square indicates that a processing facility of a specific type and capacity can be built in the corresponding node. The main results then reflect the processing capacities of the prospective facilities. The existing processing plants and landfills have fixed gate fees set with respect to their economic sustainability. Transportation cost was fixed at 0.4 EUR/(km·t). Correction functions are in this example considered only in the case of WtE plants, while cement mills use pre-set limits on LHV of the waste mixture (which, ultimately, is the reason why only other combustible waste can be processed there). Landfilling, of course, is independent of waste LHV.

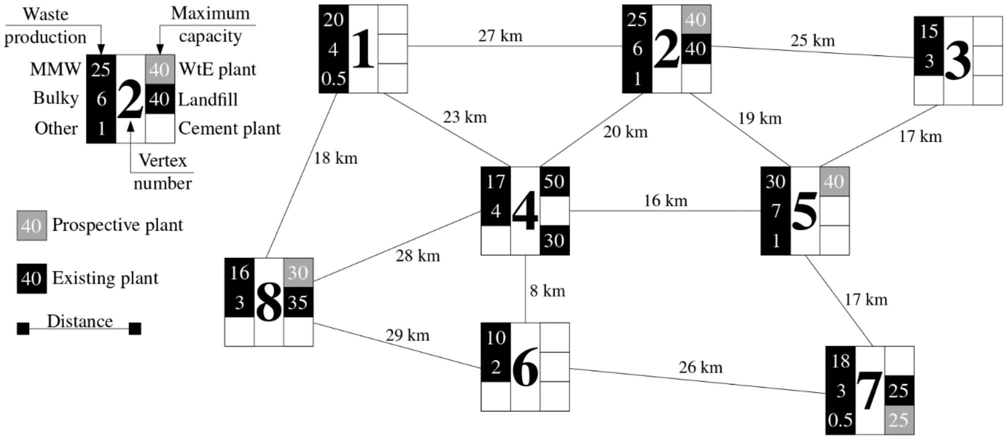

Figure 3: Input traffic network for the discussed example

The results yielded by the optimization model are shown in Figure 4 together with the actual processing capacities and network flows. In total, 64 % of waste is processed locally (at its origin) with the remainder being transported to other facilities. Individual commodities were processed as follows:

- MMW: 40 % WtE, 60 % landfill;
- Bulky waste: 73 % WtE, 27 % landfill;
- Other combustible waste: 100 % cement plant.

As for total cost allocation, the model yielded the following: transportation 4.1 %, processing in the existing facilities 73.9 %, investment and operating costs due to new facilities being built 26.6 %, LHV corrections – 4.5 %, penalization for not meeting the capacities of the existing WtE plants 0 %.

It is obvious that with the current, financially oriented setup, the model favors the utilization of waste mixtures with the highest LHV possible, while all other components are landfilled. The model also suggests making full use of the existing facilities and only then consider the prospective ones (which is confirmed by the zero penalization for not meeting the capacities of the existing WtE plants). This is why in nodes 2, 7, and 8 no investments in new facilities are proposed. The only exception is node 5, where only a portion of the maximum feasible new processing capacity is capitalized on. Construction of the prospective cement mill in node 7 was not suggested because of the low amount of waste with the highest LHV (it all is processed in node 4). From the cost allocation, one can deduce that the model cannot influence the gate fees in the existing facilities. On the other hand, significant savings is possible in transportation, because in the results it constitutes only a small fraction of the total cost. LHV correction is negative, which means that in the WtE plants in nodes 4 and 5 it was possible to reach optimum conditions even with the waste mixture having higher-than-reference LHV.

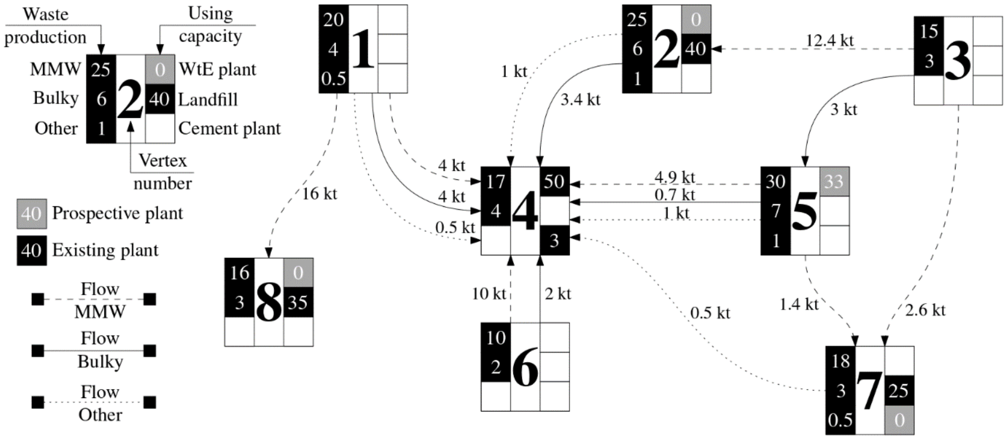

Figure 4: Results obtained using the present model

It is obvious that with the current, financially oriented setup, the model favors the utilization of waste mixtures with the highest LHV possible, while all other components are landfilled. The model also suggests making full use of the existing facilities and only then consider the prospective ones (which is confirmed by the zero penalization for not meeting the capacities of the existing WtE plants). This is why in nodes 2, 7, and 8 no investments in new facilities are proposed. The only exception is node 5, where only a portion of the maximum feasible new processing capacity is capitalized on. Construction of the prospective cement mill in node 7 was not suggested because of the low amount of waste with the highest LHV (it is all processed in node 4). From the cost allocation, one can deduce that the model cannot influence the gate fees in the existing facilities. On the other hand, significant savings is possible in transportation, because in the results it constitutes only a small fraction of the total cost. LHV correction is negative which means that in the WtE plants in nodes 4 and 5 it was possible to reach optimum conditions even with the waste mixture having higher-than-reference LHV.

5. Conclusions

This paper presents a thermochemical properties-aware optimization model which can serve as a supporting tool in waste management decision making. The main benefit is that it considers several waste fractions with varying LHV and, in general, the heterogeneity of MMW. Optimum operating conditions of WtE plants are taken into account, because they play an important role in the planning of new plants and their locations. Feasibility of the model in a reasonable time frame was ensured by linearization using the SOS2 variables. The discussed approach was tested using a suitable small-scale case. For the presented instance, it has been suggested to processed 64 % of waste directly at its production nodes. This ratio is given by the boundary conditions and input parameters of the modelled task. Another crucial output evaluates the proportion of the treatment options for the considered waste types. Future development will focus on the extension of the mathematical model so that large-scale, real-world cases can be solved efficiently. Such cases can include scenario-based LHVs instead of mean values and consider variable waste compositions in different geographical regions. The inclusion of not only the thermochemical properties of the waste but also the physical parameters can influence this issue. Another extension could involve environmental criteria which would significantly limit landfilling.

Nomenclature

$e \in E$	set of edges	$i \in I_V \subset I$	subset of nodes – facilities using lower heating value of waste
$i \in I$	set of nodes		
$i \in I_P \subset I$	subset of nodes – prospective plants	$k \in K$	SOS2 linearization points
$A_{e,i}$	incidence matrix, –	$P_{i,k}^{pro}$	parameter determining the processing fee in a prospective plant, EUR
C_i	plant capacity, kt		
D_e	edge length, km	P^{trans}	transportation cost, EUR/(kt·km)
P_k^{pen}	correction parameter, EUR	P_i^{treat}	treatment cost, EUR/kt
x_e	the amount of waste transported along the edge, kt	$\mu_{i,k}^{pen}$	linearized correction function, –
		$\mu_{i,k}^{pro}$	linearized cost at a prospective plant, –

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