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An MINLP reconstruction of networks for the collection, recycling, treatment and disposal of municipal solid waste

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Abstract

A mixed-integer nonlinear programming (MINLP) model is proposed for the reconstruction of networks dealing with municipal solid waste (MSW) within both rural and urban communities. It is based on long-term interregional or even cross-border profit optimization and optimal centre allocation for waste collection, recycling, treatment and disposal. The solution obtained indicates that scientific savings and additional income can be obtained which at a break-even point can reduce residence's payment for waste, by up to 25%.

Keywords: MINLP model, superstructure network, MSW.

1. Introduction

Recycling of waste to recover useful materials, and recycling energy from this waste by incineration is a sustainable way of dealing with MSW. The objective of overall MSW management is to propose optimal MSW management networks, where it is important to look at the broader picture including processes such as waste collection, transportation, treatment, recycling, the selling of secondary material and energy, and the final disposal. Among these processes complex and nonlinear interactive relationships exist which require continuous and discrete decisions, therefore MINLP is the most suitable form of programming to solve such problems. A similar problem for the recovery of hazardous material has been solved by the MILP model of Duque et al., 2006. Most of the developed methods for MSW management have been simplified complex models, presented as liner programming (LP) models. Or et al. (1993) create a linearization of nonlinear model in order to obtain a pseudo-linear programming model with a piecewise linear objective function. Huang (1998) developed an integral nonlinear programming model (INLP), where system costs present economies-of-scale effects. In order to handle uncertain parameters a simplified LP model was transformed into an NLP model when planning MSW management (Yeomans et al., 2003). A universal solution algorithm of the INLP model was proposed by Wu et al. (2006). One of the most important objectives of this contribution is to consider continuous and discreet decisions explicitly and simultaneously within the MINLP model's formulation, for the synthesis of new or the reconstruction of existing MSW networks. It provides a useful methodological basis for setting-up the efficient management of MSW at regional level, and provides insight into the synergy associated with cross-border MSW management cooperation.

2. Optimal discrete-continuous MSW network optimization

Basic principles suitable for optimal MSW management are considered in the model, based on the amount and composition of MSW and the requirements of various processing and disposal techniques. The most important motivation for cross-border optimization lies in the economy-of-scale effect: there are different unit costs for the different capacities of different facilities – the larger the process or disposal capacity, the less the unit costs.

2.1. Model formulation

An optimal model for total collection and treatment centre allocation has been developed. The proposed model relies on non-liner fixed charge terms, which give rise to MINLP and can be used to optimize networks for collection and processing wastes or disposing of them harmlessly over a long period. The proposed model can be applied as a synthesis model for the synthesis of a new optimal allocation network or as a reconstruction model, if both new and existing centres are included in the superstructure. The objective function contains both cost and revenue terms, where costs are divided into three categories: i) transportation costs, ii) fixed and variable costs for collection centres and iii) fixed and variable costs for recycling, treatment and disposal centres. The investment costs which are considered in the objective function within its fixed costs are considerably higher for a new centre than those of existing centres. The objective function can be defined as an annual profit (PROF), Eq. 1 or, even better, as the net present value (NPV), Eq. 2.

$$
\begin{aligned}
\text{Max} \quad PROF = & \sum_{k}\sum_{SM} c_{SM} \cdot Q_{SM,k} + \sum_{k}\sum_{EN} c_{EN} \cdot Q_{EN,k} + \sum_{k}\sum_{j} c_{j} \cdot Q_{j,k} \\
& - \left(\sum_{j}\sum_{l} c^{TR} \cdot D1_{j,l} \cdot Q_{j,l} + \sum_{l}\sum_{k} c^{TR} \cdot D2_{l,k} \cdot Q_{l,k} + \sum_{l} c^{INV}_{fix,l} \cdot w_{l} \right) \\
& - \left(\sum_{j}\sum_{l} c^{TR} \cdot D1_{j,l} \cdot Q_{j,l} + \sum_{l}\sum_{k} c^{TR} \cdot D2_{l,k} \cdot Q_{l,k} + \sum_{j}\sum_{k} c^{TR} \cdot D3_{j,k} \cdot Q_{j,k} \right. \\
& + \left. \sum_{k} \left(c^{INV}_{fix,k} \cdot z_{k} + c^{INV}_{var,k} \cdot Q_{k}^{\,c^{INV}_{exp,k}} \right) + \sum_{k} c^{OBR}_{var,k} \cdot Q_{k} \right)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\text{Max} \quad & NPV = -I + F_{C} f_{PA}\left(r_{d}\right) \\
& \text{s.t.} \\
& h(Q) = 0 \\
& g(Q) \le 0 \\
& \sum_{k \in TC} z_{k} = 1 \quad \wedge \quad z_{k} \in \{0,1\}^{m} \\
& Q \in R^{n}
\end{aligned} \tag{2}
$$

In Eq.(1) PROF represents annual profit (€/yr), $Q_{SM,k}$ is the amount of secondary material for recycling at k-th treatment centre (TC), $Q_{EN,k}$ is the amount of energy produced at k-th TC, $Q_{j,k}$ is the amount of waste transported from community j to k-th TC, $Q_{j,l}$ is the amount of waste transported from community j to l-th collection centre (CC), $Q_{l,k}$ is the amount of waste transported from l-th CC to k-th TC, Q_k is the amount of waste that must be treated at k-th TC, $D1_{j,l}$, is the distance between community j and l-th CC, $D2_{l,k}$, is the distance between l-th CC and k-th TC, $D3_{j,k}$ is the distance between community j and k-th TC, c_{SM}, c_{EN}, c_j, c^{TR}, $c^{INV}_{fix,l}$, $c^{INV}_{fix,k}$, $c^{INV}_{var,k}$, $c^{INV}_{exp,k}$ and $c^{OBR}_{var,k}$ represent cost coefficients for secondary materials, energy produced at TC, transporting costs, annualized investment cost plus operating costs of treatment facilities, respectively. w_l represents the binary variable for l-th CC and z_k represents the binary variable for k-th TC. In Eq. (2) I is the investment cost, F_C is the net cash flow and $f_{PA}(r_d)$ is the annuity present worth factor corresponding to the discount rate r_d.

2.2. Network superstructures

European legislation forces our communities to create an integrated MSW management system so that the generated waste can be reduced, reused or energy can be generated and, consequently, the dependence on landfills can be minimized. With the use of MINLP optimization for MSW management networks, each community can be, in principle, connected to any centre located in any community (Fig.1). Note that in Figure 1 these arrows are not shown in the superstructures.

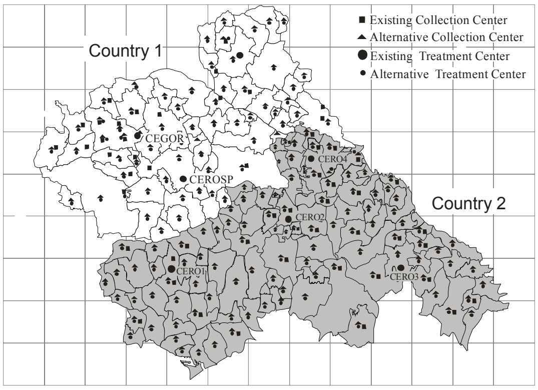

Figure 1: Network superstructure for waste collection and treatment.

3. Case Study

Our research is based on investigating the amount and composition of MSW for two regions in Country1 and four regions in Country2, which are divided into rural and urban communities. Management of approximately $0.268 \cdot 10^6$ t/yr generated waste, which must be collected and disposed of with minimal costs, must be developed. Transportation cost coefficients from communities to the TC is 0.71 €/(t·km). A 70 % fraction of the generated waste is currently mixed waste and 30 % of wastes are separated fractions such as paper, plastic, metal, glass, and can be recycled and sold as secondary materials. Some additional revenues from waste can be gained if compost, electricity and steam could be sold. Important revenues for TC are a resident's specific charge (100 €/t) and an industry charge (150 €/t) for transport and landfill.

3.1. Cross-border collection and treatment centre network without incineration – optimized with annual profit function (Eq. 1):

An MINLP model for an entire superstructure (Fig. 1) of MSW management without incineration has been developed and MINLP optimization was performed when an appropriate trade-off was established between the revenue from recycling of the useful materials/energy and the transportation/processing costs, including the investment cost of new alternatives. The investment costs of composting, mechanical biological treatment, incineration and landfill were defined by mixed-integer nonliner terms, which were included in the MINLP optimization and the annualized profit function (Eq. 1). Optimization for three alternatives has been executed for both countries, separately, and for both of them together:

a) Optimization of the existing CC and TC network structure.
b) Synthesis of a new optimal allocation network comprising only the locations of the new CC and TC alternatives.

c) Reconstruction of the existing network comprising both locations of the existing and new CC and TC alternatives.

Table 1: Annual profit without incineration for collection and treatment centre network.

		a) Existing	***b) New***	***c) Reconstruction***
Country 1	***Annual profit***	**0.328 M€/a**	**– 0.391 M€/a**	**0.688 M€/a**
	No. of CC/TC	*23 exi. CC/ 3exi. TC*	*22 new CC/ 3 new TC*	*17 exi. + 6 newCC/ 1exi. + 2 new TC*
Country 2	***Annual profit***	**– 5.305 M€/a**	**– 3.282 M€/a**	**– 3.151 M€/a**
	No. of CC/TC	*33 exi.CC/ 4exi. TC*	*26 new CC/ 3 new TC*	*20 exi. + 8 newCC/ 1exi. + 2 new TC*
Both countries	***Annual profit***	**– 4.894 M€/a**	**– 4.193 M€/a**	**– 2.292 M€/a**
	No. of CC/TC	*56 exi. CC/ 7exi. TC*	*48 new CC/ 6 new TC*	*37 exi. + 14 newCC/ 1exi. + 5 new TC*

The solutions for all the optimization alternatives point out the trade-off between investment, operation and transportation costs and revenues obtained from recycling useful materials and energy, and resident's payments for waste treatment. The best optimal result for annual profit without the incineration of – 2.292 M€/a was obtained for the reconstruction of collection centre networks and gives an optimal location network of *17 existing and 6 new CCs and 1 existing and 2 new TCs* (Tab. 1). Resident's and industrial charges should increase by 10.7 % in order to reach break-even point.

3.2. Reconstruction of cross-border collection and treatment centre network with and without incineration

To obtain a sustainable way of dealing with MSW over a longer time period, optimization of objective function as the net present value is used for a time period of 20 years and a discount rate of 7 %. For optimal network without incineration at 30 % of collected separated fractions NPV of – 15.740 M€ (Tab. 2) is obtained for reconstruction of the existing network and comprises: 10 *existing CCs* and *41 new CCs* and 6 *new TCs*. With the incineration of waste a new optimal network was obtained with NPV of 40.158 M€ comprising: 10 *existing and 41 new CCs* and 6 *new TCs and 1 incineration centre.* To reach break-even point, resident's and industry prices for waste treatment can be decreased by 20.2 %. If in the future more waste is collected as separated fractions e.g. up to 50 %, the NPV will be increased to 57.310 M€.

Table 2: Optimal results obtained for superstructure of MSW.

Separated fractions of MSW (%)	***Annualized profit***		***Net present value***	
	with incineration	without incineration	with incineration	without incineration
30 %	4.292 M€/yr	– 2.292 M€/yr	40.158 M€	– 15.740 M€
40 %	5.617 M€/yr	– 1.967 M€/yr	51.757 M€	– 12.684 M€
50 %	5.864 M€/yr	– 1.093 M€/yr	57.310 M€	– 7.268 M€

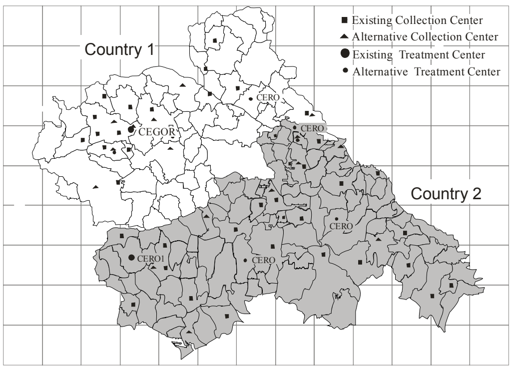

Figure 2: Optimal cross-border network for waste handling.

Conclusion

Optimal interregional collection and treatment centre networks were obtained by MINLP where an appropriate trade-off between revenue from the recycling of useful materials, energy and compost, transportation and processing costs, including investment costs for both existing and new alternatives was established. Due to the economy-of-scale effect in a cross-border cooperation, the higher percentage of collected separated fractions and energy produced by incineration, a significant decrease in resident's and industry charges for waste treatment could be obtained (27%).

References

1. Yeomans, J.S., Huang, G.H., Yoogalingam, R., 2003. *Journal of environmental Informatics*. 2 (1), 11-30.
2. Or, I., Curi, K., 1993. *Waste Management & Research* 11, 4-11.
3. Huang, G.H., 1998. *European Journal of Operational Research* 107 (1), 137-158.
4. Wu, X.Y., Huang, G.H., Liu, L., Li, J.B., 2006. *European Journal of Operational Research* 171, 349-372.
5. Duque, J., Barbosa-Povoa, A.P.F.D., Novais, A.Q., 2006. *ESCAPE-16and PSE-9 Computer Aided Process Engineering*, 1797-1802.