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Integrated Process Design Optimization Accounting for Co-Digestion of Sludge and Municipal Solid Waste

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Abstract

This work presents an optimization model for the integrated design of waste treatment facilities, accounting for co-digestion of sludge and municipal solid waste. The superstructure of alternatives includes anaerobic digestion under mesophilic or thermophilic conditions, composting, recycling, and final disposal in a landfill. Anaerobic digesters can be fed with different mixing ratios of sewage sludge (*SS*) and the organic fraction of municipal solid waste (*OF*). A mathematical formulation derived from disjunctive programming is proposed to find the optimal process design. It comprises nonlinear equations to estimate digestion yields according to substrate mixing ratios. Results show that joint treatment increases the profitability, especially in small cities. Co-digestion of *SS* and *OF* leads to an integrated waste-to-energy process that maximizes the economic value of waste by producing electricity, heat and fertilizer.

Keywords: Co-digestion; Waste; Optimization; Superstructure; Process Design.

1. Introduction

The volume of urban waste continues to increase as a result of population growth, economic development and urban spread. Municipal solid waste and sewage are the main waste generated in urban centres, and treatment in many countries begins to be strictly required by local laws. Then, a sustainable and economical solution to convert waste into valuable products is needed. The most commonly applied technologies to treat urban waste are anaerobic digestion (*AD*), composting, recycling, and final disposal in landfills. Because of their relatively low investment cost, landfills continue to be one of the most used methods despite their significantly high potential to pollute the environment. *AD* is a mature technology that has been widely investigated as it allows the use of biogas as renewable energy and digestate as fertilizer. In turn, composting produce a marketable final product that without detectable levels of pathogens can also be applied as fertilizer.

There are many mathematical models for simulating *AD* process dynamics (Lauwers, 2013). Some works have focused on determining the optimal feedstock mixing ratio that maximizes methane production rates (Alvarez et al., 2010). Recent results suggest that co-digestion can increase the productivity from the sole substrates (Nielfa et al., 2015), thus offering the opportunity of taking advantage of an integrated treatment of urban waste. However, there are very few papers addressing the selection of waste treatment alternatives that also include the optimization of the *AD* design (Drobez et al., 2009). And none of them account for co-digestion. To overcome this, we propose a novel mathematical formulation derived from disjunctive programming to find the optimal process design. It comprises binary variables accounting for the selection of treatment alternatives, and nonlinear equations to estimate anaerobic digestion yields according to substrate mixing ratios. The model is able to choose the most convenient *AD* co-feeding ratio. Solutions are assessed by means of an economic objective function including both capital and operating expenditures. The analysis is developed for different sizes of cities to evaluate the economies of scale of the treatment facilities.

2. Problem definition and mathematical formulation

The daily production of municipal solid waste (Q_{MSW}) is estimated from the average generation of waste per capita. The composition of *MSW* is categorized as 50% organic fraction (Q_{OF}), 38% recyclable material (Q_R), and 12% others, non-recyclable (Q_{OT}). The daily generation of sewage sludge (Q_{SS}) is also proportional to the size of the city. The superstructure of waste treatment alternatives (Fig. 1) includes anaerobic digestion (*AD*) under mesophilic or thermophilic conditions, composting, recycling, and final disposal in a landfill. To model the *AD* superstructure, a set of single anaerobic digesters ($b \in B$) is proposed for each possible combination of temperature conditions ($d \in \{d_1$: *mesophilic*; d_2: *thermophilic*$\}$) and mixing ratios ($m \in \{m_1$: *0-100*, m_2: *100-0*, m_3: *80-20*, m_4: *60-40*, m_5: *40-60*, m_6: *20-80*$\}$, given in %*OF* - %*SS*). The maximum number of digesters proposed in the set *B* is a critical model parameter. Binary variables $W_{d,m,b}$ are used to determine whether or not the digester *b*, under temperature range *d*, fed with waste ratio *m* will be installed ($W_{d,m,b}=1$). In the following sections we present the main groups of equations that model the integrated waste treatment superstructure.

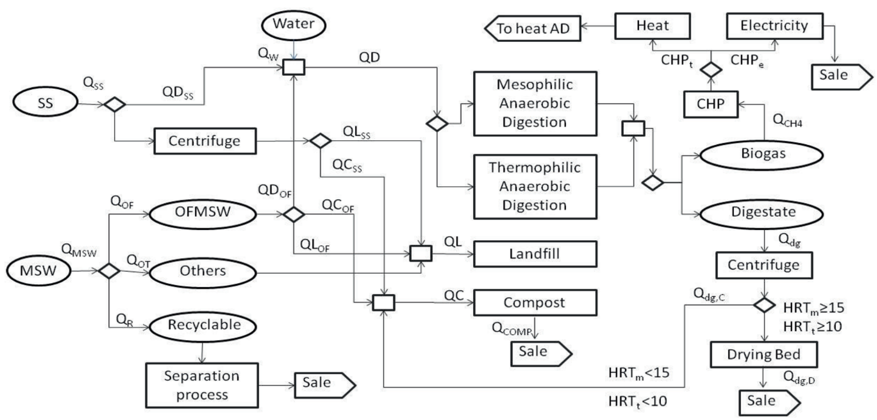

Figure 1. Superstructure approach for the optimization of waste treatment alternatives

2.1. Mass balances

The daily generation of *OFMSW* can be sent to three processing alternatives (Eq. 1): composting plant (QC_{OF}), one or more specific anaerobic digesters ($QDof_{d,m,b}$) or simply to landfill (QL_{OF}) as often seen in practice. The recyclable fraction of *MSW* (Q_R) is treated in a separation plant, and non-recyclable material (Q_{OT}) is directly sent to landfill. Furthermore, sewage sludge flow (Q_{SS}) can be disposed of in landfill sites (QL_{SS}), used as feedstock in any individual *AD* ($QDss_{d,m,b}$), or can be composted (QC_{SS}) if allowed by local regulations (European Parliament, 1986). The *SS* sent to compost or landfill is previously dewatered by centrifugation.

$$Q_{OF} = \sum_{d.m.b} QDof_{d,m,b} + QLof + QCof \ ; \ Q_{SS} = \sum_{d.m.b} QDss_{d,m,b} + QLss + QCss \tag{1}$$

Typically, *AD* total inflow requires 8% of dry matter content. As *OF* substrate usually presents a higher value, it is necessary to dilute some inflows with water ($QW_{d,m,b}$). The dry matter content of mix *m* is a constant value given by TS_m (Eq. 2).

$$QD_{d,m,b} \cdot 0.08 = \left(QDof_{d,m,b} + QDss_{d,m,b}\right) \cdot TS_m \tag{2}$$

The digestate produced in each *AD* is centrifuged and sent to compost processing ($Qdg,C_{d,m,b}$) if the corresponding hydraulic retention time $HRT_{d,m,b}$ is smaller than 15 or 10 days for *mesophilic* or *thermophilic* conditions, respectively. If it is larger, the digestate ($Qdg,D_{d,m,b}$) is sent to drying beds (*DB*) and sold as organic fertilizer.

For every single *AD* the total inflow $QD_{d,m,b}$ is determined by Eq. (3). In turn, Eq. (4) accounts for landfill (*QL*), composting (*QC*), and drying bed (*QDB*) input flows.

$$QD_{d,m,b} = QDof_{d,m,b} + QDss_{d,m,b} + QW_{d,m,b} \tag{3}$$

$$QC = QC_{OF} + QC_{SS} + \sum_{d,m,b} Qdg,C_{d,m,b} \ ; \quad QL = QL_{OF} + QLss + Q_{OT} \ ; \ QDB = \sum_{d,m,b} Qdg,D_{d,m,b} \tag{4}$$

2.2. Anaerobic digestion (methane production)

The energy content of the biogas is directly related to its methane content (CH_4), which depends both on the biomass used as substrate and the retention time. The methane yield for every individual *AD* ($Q_{CH4,d,m,b}$) is approximated from a CSTR system, based on a first-order kinetic model (Linke, 2006).

$$Q_{CH4,d,m,b} = \frac{y_{d,m,b} \cdot VS_m}{1000} \cdot \left(QDof_{d,m,b} + QDss_{d,m,b}\right); \ y_{d,m,b} = \frac{HRT_{d,m,b} \cdot k_{m,d} \cdot ym_{m,d}}{HRT_{d,m,b} \cdot k_{m,d} + 1} \tag{5}$$

In Eq. (5), $ym_{m,d}$ is the ultimate methane yield achievable per unit of volatile solids in mix *m*, under condition *d*; $k_{m,d}$ is the reaction rate constant; and VS_m is the volatile solids concentration in mix *m*. The substrate characterization and the kinetic constants of the co-substrate mixing ratios are obtained from the literature (Nielfa et al., 2015). Eq. (6) ensures that, if an *AD* is selected to process mix *m*, the corresponding feeding ratio is fulfilled. Xof_m and Xss_m are the mass fractions of *OF* and *SS* in every mixing option.

$$QDof_{d,m,b} = Xof_m\left(QDof_{d,m,b} + QDss_{d,m,b}\right); \ QDss_{d,m,b} = Xss_m\left(QDof_{d,m,b} + QDss_{d,m,b}\right) \tag{6}$$

The CH_4 produced is converted into electricity and heat in a combined heat and power plant (*CHP*), with electrical and thermal yields of 33% and 55%, respectively. The electricity (*CHPe*) is sold to the grid, and the heat (*CHPt*) is used in the *ADs*.

The investment cost in a single *AD* ($C_{d,m,b}$) is a function of the volume of the digester and the *CHP* capacity (Willeghems and Buysse, 2016). It comprises the storage tank, digestate centrifuge, evaporation and air scrubber units, civil works, permits, and grid connection. It is assumed to be linearly dependent on the volume of the digester, but follows an economy-of-scale function with the CHP capacity. The operational costs

($O_{d,m,b}$) comprises annual maintenance, insurance, and heating costs. The external energy requirement to heat a single *AD* is calculated from its volume $V_{d,m,b}$, by discounting the thermal energy generation ($CHPt_{d,m,b}$). We impose a maximum volume of 4,000 m^3 and square cylinder design ($2\ r_{d,m,b} = h_{d,m,b}$). Revenues ($I_{d,m,b}$) come from electricity, organic fertilizer, and Certified Emission Reductions.

2.3. Compost, centrifuge and drying bed

We use the algorithm proposed by the EPA (1984) to size the windrow composting facility and calculate the corresponding capital (C_C) and annual operating costs (O_C). C_C includes purchase of land, site clearing, paving of composting area, purchase of windrow turning machine, and construction of unloading and mixing devices. O_C includes operational and maintenance workforce and supplies, fuel for composting and ancillary machinery. The income (I_C) derives from selling compost as organic fertilizer.

The same model (EPA, 1984) is used to size centrifuge installation (*CI*) and *DB*. The solids concentration in the dewatered digestate is 25%, and it increases to 47% in the *DB*. Capital and operation expenditures for *CI* and *DB* are represented by C_{CI}, O_{CI}, C_{DB} and O_{DB}. Revenues (I_{DB}) come from selling the resulting organic fertilizer.

2.4. Landfill and separation plant

Capital investment in landfill sites (C_L) includes the direct costs for the construction of cells, leachate treatment facilities and common infrastructure (land acquisition, offices, services, roads, etc.). Operational expenditures (O_L) are due to utilities, transportation and workforce costs. Correlations are derived from theoretical calculations of integrated solid waste management (SAyDS, 2005). No incomes are considered in this case.

The same theoretical calculations (SAyDS, 2005) are used to estimate the investment (C_S) and operational costs (O_S) of the separation plant. We consider the incomes (I_S) from selling recyclable materials (papers, plastics, glass and metals).

2.5. Objective function

The net present value (*NPV*) of the project is selected as the model objective function, as shown in Eq. (7). The set *T* comprises the annual periods of the planning horizon, whose length is 20 years. Parameter *r* represents the discount rate (13%).

$$\begin{aligned} max \quad NPV = & -C_S - C_L - C_C - C_{CI} - C_{DB} - \sum_{d,m,b} C_{d,m,b} \\ & + \sum_t \left(I_S + I_{DB} + I_C - O_S - O_{CI} - O_C - O_L - O_{DB} - \sum_{d,m,b} \left(I_{d,m,b} - O_{d,m,b} \right) \right) \cdot \frac{1}{(1+r)^{t-1}} \end{aligned} \tag{7}$$

3. Results and Discussion

The proposed mixed-integer nonlinear formulation is coded in GAMS 24.6.1 and solved on an Intel X5650-2.66 GHz processor, with 24 GB RAM. We use BARON 15.9 solver, which is able to guarantee global optimality. Four scenarios are presented along with their results in Table 1. Scenario 1 comprises a single plant to treat *MSW*, while Scenario 2 comprises a single plant to process *SS*. Scenario 3 proposes an integrated treatment by imposing the optimal mixing ratio for methane production (80% *OF* - 20% *SS*). Scenario 4 sets the full model without flow constraints, with all the possible mixing ratios allowed. Each scenario is solved for five population sizes. Table 1 summarizes landfill disposal, composting and digestion rates in tons per day. *QL/QC* rates show how much sludge goes to landfill and composting, respectively. *QD/QdgD* account for digester feed rates and direct selling of dry digestate. The volume V_{AD} (m^3) and the corresponding retention time *HRT* (days) for every *AD* are also reported in Table 1. When more than one digester show the same V_{AD} and *HRT*, the number of replicated *ADs* is given between brackets. The *NPV* is expressed in million USD.

Table 1. Optimal waste treatment designs for different scenarios and population sizes

Scenario	**Quantities**	**Sizes of cities** (in thousands of people)				
		50	*150*	*250*	*500*	*1000*
1 **MSW**	*QL / QC*	6 / 0	18 / 0	30 / 0	60 / 0	120 / 0
	QD /Qdg,D	146.2 / 44.3	438.7 / 133	731.1 / 221.7	1462 / 446	2924 / 892
	V_{AD} (*HRT*)	2540 (17.7)	3630 (17.7) 4000 (17.6)	3840 (17.1) [4000(16.1) (x2)]	[4000 (11.1) (x4)]	[4000 (11.1) (x8)]
	NPV_1	**6.96**	**29.19**	**49.76**	**109.8**	**223.1**
2 **SS**	*QL / QC*	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
	QD /Qdg,D	43 / 13	129 / 39	215 / 66	430 / 131	860 / 262
	V_{AD} (*HRT*)	422 (10)	1290 (10.2)	2170 (10.32)	228 (10) 4000 (10)	464 (10.2) [4000 (10) (x2)]
	NPV_2	**-2.87**	**0.44**	**3.8**	**11.63**	**28.06**
3 **Fixed mixing ratio (80%-20%)**	*QL / QC*	6 / 46	18 / 137	30 / 229	60 / 458	120 / 941
	QD /Qdg,D	107.9 / 33	325.2 / 98	538.8 / 163	1077.5 / 328	2033 / 618
	V_{AD} (*HRT*)	1810 (17.0)	3440 (17.2) 1970 (16.8)	[4000(15.1) (x2)]	[4000(11.3) (x3)]	[4000 (15) (x3)] [4000 (10) (x3)]
	NPV_3	**7.05**	**30.23**	**54.41**	**114.23**	**227.00**
4 **Full model**	*QL / QC*	6 / 0	18 / 0	30 / 0	61 / 0	121 / 0
	QD /Qdg,D	194.5 / 58.7	583.9 / 176	973.3 / 294	1943 / 590	3890 / 1180
	V_{AD} (*HRT*)	2960 (15.5)	3300 (16.5) 3120 (16.8) 2900 (15.4)	[4000 (12.5) (x3)]	[4000 (10.5) (x5)]	[4000 10.5) (x10)]
	NPV_4	**9.22**	**36.09**	**64.89**	**135.02**	**267.6**
NPV_4 / NPV_3		1.31	1.19	1.19	1.18	1.18
NPV_4 / [NPV_1+NPV_2]		2.25	1.22	1.21	1.11	1.07

As expected, results show that the maximum *NPV* is obtained in Scenario 4, where several *ADs* are built, selecting a mixing ratio equal to the original proportion in which *SS* and *OF* are daily produced (40% *OF* - 60% *SS*). The joint treatment of waste flows increases the profit 125% for cities with 50 thousands of people, and between 7 and 22% for larger cities, compared to the separate treatment (see NPV_4 / [NPV_1+NPV_2] ratios in Table 1). It is also observed that the optimal NPV_4 outperforms NPV_3 by 18 to 31% (see NPV_4 / NPV_3 ratios in Table 1). This is so because the excess *OFMSW* that is not sent to *ADs* is composted (larger *QC* in Table 1), which is generally more expensive than drying the digestate. Moreover, Scenario 3 yields lower benefits from energy generation. Another important result is that *ADs* are operated under thermophilic conditions, in all scenarios. The thermophilic regime is more efficient than the mesophilic in terms of the digester volume, retention time and CH_4 production, and the extra energy needed to heat the *AD* is taken from the *CHPt*, without extra heating costs.

It is interesting to note that there is almost no economy of scale when the population exceeds 250k inhabitants (see the evolution of NPV_4 with the population sizes). However, when the population is smaller, it plays a critical role. In fact, the *NPV* could be significantly increased if the waste from several small cities were treated in a common facility (without neglecting higher transportation costs). Another model capability is to select treatment alternatives with sub-optimal *NPVs*, but requiring lower investment to adapt to the budget of the cities. For a city of 150k inhabitants, for instance, the model can be restricted to suggest a single *AD*. In that case, the remaining waste should be sent to compost. Capex is reduced by 33% while the corresponding *NPV* is reduced by 20.6%. Note that in Scenario 4, *AD* design variables (V_{AD} and *HRT*) are practically identical for every digester, meaning that regardless of the size of the city, the optimal solution tends to equally distribute substrate flows between *AD*s.

In terms of the computational burden, almost all of the problem instances are solved to global optimality (10^{-6} gap) in less than 700 CPU s. However, for larger cities (≥ 500k) under Scenarios 3 and 4, the optimal solution is not guaranteed after 3,600 CPU s due to the growth in the model size derived from a larger number of elements in the set *B*.

4. Conclusions

We developed an MINLP mathematical formulation to find the optimal process design for integrated urban waste treatment. Results show the convenience of anaerobic digestion when compared to landfilling and composting. In addition, the economic analysis suggests that digesters should operate at thermophilic conditions, being fed by the same proportion in which municipal solid waste and sewage sludge are daily produced (40% *OF* - 60% *SS*) to maximize profitability. Regardless of the size of the city, joint treatment outperforms separate processing, increasing profits. Interestingly, the optimization of the process superstructure suggests a different mixing ratio than that known to maximize methane production and digestion efficiency (80% *OF* - 20% *SS*).

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