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Networks for Utilising the Organic and Dry Fractions of Municipal Waste: P-graph Approach

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Minimising the demand for fossil fuels and the greenhouse gas footprints is of high priority for sustainable development. This is true for all societal aspects – including research and development. Waste-to-Energy (WtE) networks are regarded as one of the potential contributors to solving this problem by applying a win-win strategy for simultaneously minimising the landfilled waste, fossil fuel demand and the associated footprints. A critical aspect for the success of a Waste-to-Energy network is to account for the spatial challenges posed by the distributed nature of the waste generation and the energy demands, where the size of the processing facilities and the served areas should be simultaneously optimised. The current work proposes concepts and procedure for targeting these capacities and sizes as the first step in the WtE network synthesis, employing Process Integration and P-graph. An illustrative case study is provided, illustrating the procedure and its application.

1. Introduction

Municipal Solid Waste (MSW) has a diverse composition (Fodor and Klemeš, 2012). That work has analysed the technologies for utilising waste as fuel. MSW contains a sizeable organic fraction, part of which is moist. A key property of MSW management is the distributed nature of the waste generation in terms of area (Varbanov et al., 2012) – similar to biomass from crops or natural resources. Household energy demands are also distributed – pointing to an important property of Waste to Energy (WtE) networks.

It has been previously shown that distributed WtE treatment can be economically viable, including thermal waste treatment – e.g. of sewage sludge (Stasta et al., 2006). MSW incineration is also widely practised. However, these treatment options are considered only for centralised, distributed treatment and energy generation using anaerobic digestion or gasification are usually left out. This reveals that it is important to develop a framework for synthesising municipal WtE networks, including the collection, transportation and treatment of waste followed by energy generation and distribution to customers. An interesting step in this direction is the network-flow based model for optimal allocation of capacities among waste generation areas and waste incineration facilities (Šomplák et al., 2017). However, this still leaves open the question of the optimal size of the WtE facilities.

The current work uses P-graph as the targeting and process synthesis tool. This is a combinatorial optimisation framework aimed at optimising process networks. It is effective in handling problems with high combinatorial complexity significantly reducing the related computational burden, applying the Accelerated Branch and Bound algorithm (Friedler et al., 1996). The framework has been more recently presented in detail by Klemeš et al. (2010). The software tool used is P-graph Studio (2017). The procedure is illustrated with a case study.

2. Targeting

Evaluating the potential for emission reduction and renewable energy generation from urban and neighbouring areas can be performed in several stages. While detailed optimisation of the MSW network is possible, it requires data collection on the waste supply locations, potential waste processing locations, the amounts of

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waste generated, quotes of transportation and processing equipment, assembly and installation. While this activity is necessary at final design stages, it is resource and time intensive.

To justify such detailed studies, targeting (preliminary evaluation) can be performed. Targeting uses a simplified model of the network, based on favourable assumptions in terms of system topology, costs, emissions and energy efficiency. If based on the favourable assumptions, the evaluation shows a potential profit and/or benefit in terms of emission reduction or energy substitution, the detailed design can be carried out. In the opposite case, it would be guaranteed that no benefit can be obtained and the detailed design would be unnecessary.

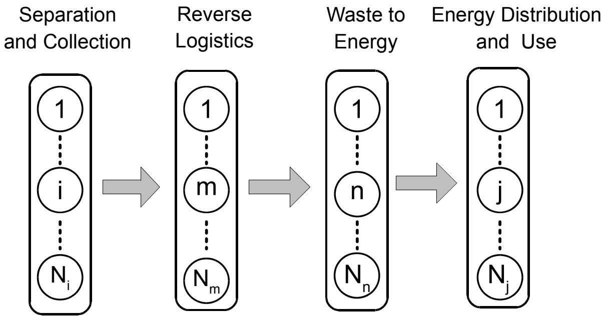

Figure 1: Waste to Energy processing workflow

2.1 General workflow

It is assumed that the typical procedure for waste collection and processing (Figure 1) is applied:

- Separation and Collection – It is assumed that the separation takes place at the source and the resulting fractions are the dry waste, intended for landfill, and organic waste, suitable for anaerobic digestion. The collection takes place at the locations where the waste was generated and separated.
- Reverse Logistics (Hawks, 2006) – This stage includes the process of transporting the collected waste to a central location. It is important to note that this activity poses a very specific case of the spatial optimisation problem, typical for the harvesting of waste-based resources and renewable energy resources. The commonality of the problem comes from the distributed nature of these resources.
- Waste-to-Energy – This is the stage of processing the useable organic and dry waste fractions to generate heat and power. This normally takes place at a single location.
- Energy Distribution and Use – This involves the distribution of the generated energy to customers substituting energy demand from conventional energy sources, such as natural gas and grid electricity.

2.2 Targeting model setup

A waste collection zone may have various shapes. A typical example can be seen in Figure 2a. The WtE network is targeted using a plant-centric viewpoint. This means that the WtE conversion plant is regarded as the centre of the considered system. The targeting approach evaluates what number of inhabitants can be served by it, by processing their waste and satisfying a portion of the residential energy demands.

Depending on the position of the WtE plant, there can be various waste transportation routes. For deriving targets for processing cost, energy generation and emissions from the potential WtE network, the following approximations are defined for the simplified plant-centric approach shown in Figure 2b.

(a) A circular Equivalent Collection Zone (ECZ) is considered (Figure 2b), having the same total waste supply, as the real waste collection zone. For this ECZ, it is also assumed that the waste generation is uniformly distributed at collection points over the equivalent circular area. The equivalent circular area may be based on the total area of the real collection zone.

(b) For obtaining the upper bound on targeted performance, which corresponds with the lower bound on cost and/or GHG emissions, it is necessary to minimise the average transport distance. As a result, the ECZ concept assumes that the WtE plant is in the centre of the circular area.

(c) The waste transport features a set of single paths, starting at the various collection points inside the circle and ending at the centre at the WtE plant. Normally, the waste collection and transportation routes are longer than the sum of such single paths, which ensures the bounding property of the derived estimates for fuel, costs and emissions.

2.3 Separation and collection model

This stage is modelled lumped with the waste generation – following from the assumption of waste separation is performed at the source. The model applies a simple splitter operation taking the total waste generated and splitting it into an organic waste fraction (OWF, digestible) – to be supplied to the anaerobic digesters, a dry fraction (DF) suitable for incineration, and the remainder as landfill fraction.

2.4 Waste transportation (reverse logistics)

The overall waste Transportation Cost, TC, is modelled as a sum: waste transportation and handling Eq(1)

$$TC = \left(\frac{2}{3\sqrt{\pi}} \cdot A \cdot e_t \cdot p_f \cdot P_{den}^{-0.5} \cdot \hat{m}_{w,gen}^{-0.5}\right) m_{tot}^{1.5} + (\hat{c}_{hand}) m_{tot} \tag{1}$$

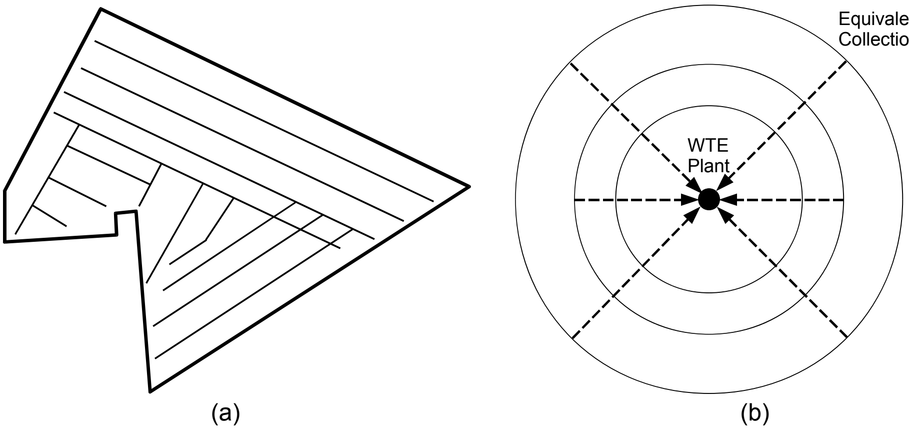

Figure 2: (a) an example of a typical shape of waste collection zone for a Greek town (after Chalkias and Lasaridi, 2011), (b) Targeting approximation of waste collection area

The first term in Eq(1) is the transportation function of the waste material. It is assumed proportional to the product of total waste mass (m_{tot}) and average distance to/from the central processing hub. According to the ECZ representation, the average distance depends on the square root of the collection area, which, with a uniform distribution of waste, relates to the total mass. Combining these relationships, results in the transportation cost term proportional to the waste mass flow to the power of 1.5. In addition, the term includes the energy use for transportation (e_t), the price of fuel (p_f), the population density (P_{den}), the waste generation rate per capita ($\acute{m}_{w,gen}$), and targeting parameter A. When A is set at unity, Eq(1) determines the absolute minimum cost of waste transportation. This is useful for setting a theoretical bound on the transportation cost but is not likely to be practical. In this paper, A is set at 1.5, which helps determine realistic performance targets.

The second term in Eq(1) relates to the waste handling. This is directly proportional to the waste amount (m_{tot}) and the average unit cost of handling ($\hat{c}_{hand}$). It is independent of the distance the waste needs to travel.

In the P-graph implementation, the transport operations are linearised, derived from Eq(1), minimising the error. The GHG emissions from transport are modelled as proportional to the distance and waste mass.

2.5 Waste-to-energy for distribution and use

Two processing routes are considered: (a) anaerobic digestion combined with CHP generation and (b) incineration, generating only heat. The digester takes as feed the OWF flows are transported from the source locations while generating biogas and solid residues. The biogas is passed to the CHP units and the residues to landfill. The CHP units generate heat and power. The incineration units take the DF stream transported from the source locations and produce useful heat. The generated heat in both cases is passed to hot water as the energy carrier. The local demands for heat and power are defined as model parameters. Simple balancing is performed, of the generation and the demands, resulting in either import or export from/to the market.

2.6 Model implementation

The overall model is implemented using the P-graph Framework (Friedler et al., 1996) in P-graph Studio (2017). This tool is particularly suitable for scoping and targeting models involving processing networks, offering a simple interface, streamlined modelling, fast computation, and combinatorial efficiency.

The performance of each operating unit is specified by the user by means of proportional conversion ratios between input and output streams. The further specifications include:

- Maximum number of inhabitants generating waste
- Heat and power demands of inhabitants
- Prices and emission factors of required transport fuels and conventional energy sources
- Waste composition in terms of organic waste fraction, dry fraction, and landfill fraction
- Performance characteristics of the energy generation technologies, e.g. boilers and gas engines

The completed model is subjected to optimal Process Network Synthesis minimising total cost.

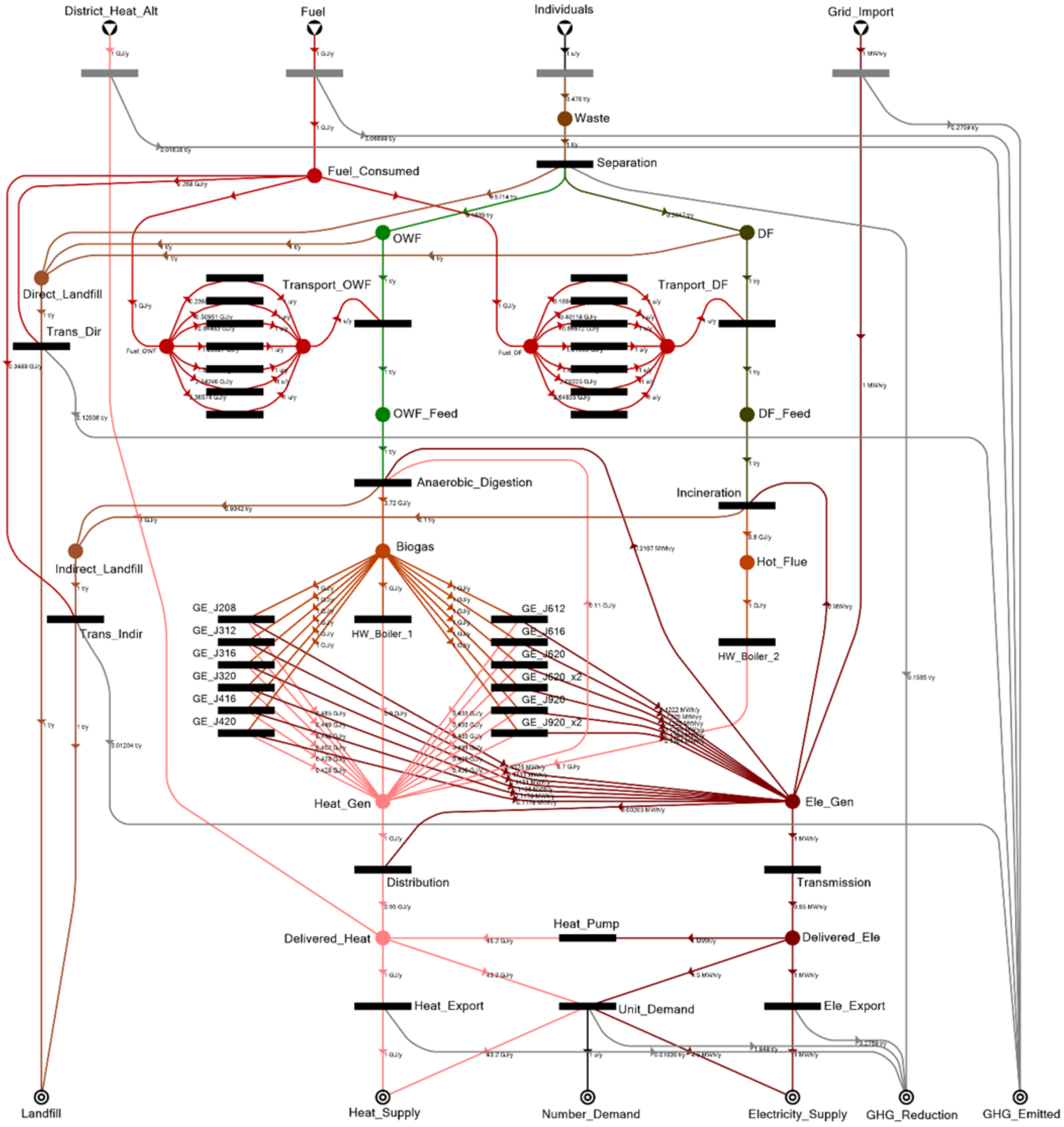

Figure 3: Visual superstructure of the Waste-to-Energy problem in P-graph Studio

3. Case study

The concepts and the model have been implemented in a case study (Figure 3), to evaluate and demonstrate their performance for a typical European city with a population density of 2,500 inhabitants/km^2. An ECZ is considered, for which 200,000 inhabitants generate waste, which is processed to generate heat and power demand to satisfy a portion of the total inhabitants. The study estimates 476 kg/y of waste with the composition of 16.4 % OWF, 26.5 % DF, and 57.1 % other (Eurostat, 2017).

In the superstructure, the household waste is separated at the source. The OWF and DF are transported to a central processing hub with transport cost estimated from Eq(1) where the price of diesel is 28.66 €/GJ (Eurostat, 2017) and the transportation energy requirement is 0.2 GJ/(t km) (Varbanov et al, 2012). The remainder of waste follows the conventional path to landfill at a cost of 120 €/t based on adjusting comprehensive data from 2002 to the present (Eurostat, 2017). The OWF is converted to biogas in anaerobic digesters, with biogas output of 3.72 GJ/t of OWF (Berglund and Börjesson, 2006) and the dry fraction generates hot flue gas using incineration. The biogas may be fed to one of 10 discrete CHP gas engine models (GE, 2017) and/or to a boiler with an overall efficiency of 90 %. The hot flue gas from incineration generates hot water with 70 % efficiency. Heat and electricity transmission losses are assumed 5 % and the pumping cost of hot water is 1.5 €/t. Heat pumps with a COP of 4.5 at the point of use present the option to convert power to heat for satisfying household demand. Heat (43.2 GJ/y) and power (4.5 MWh/y) are returned to fulfil some household energy demands (Varbanov et al, 2012) while excess heat or power may be exported for 20.2 €/GJ of heat and 205.2 €/MWh of electricity (Eurostat, 2017). Greenhouse gas (GHG) emissions are explicitly quantified in the model in terms of emissions given the new energy supply design using waste-to-energy as well as the effective emissions reduction from replacing fossil fuel energy sources represented by the district heat system and electricity grid. The GHG emissions price is set at 5.0 €/t, which is typical of the spot price over the past year.

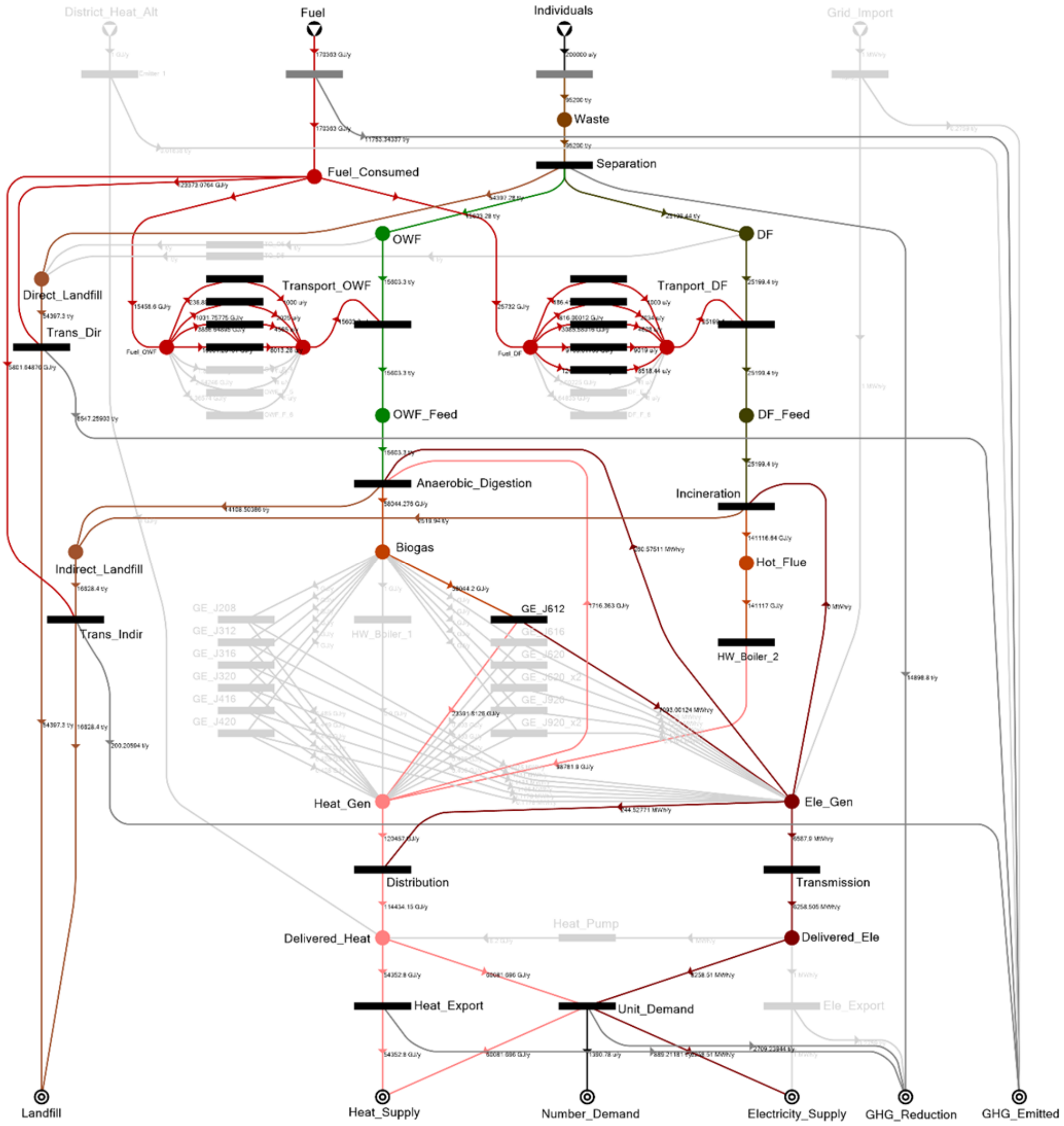

Figure 4: Optimal network in P-graph representation

The optimal network design targeted using the P-graph model is presented in Figure 4. For the proposed targeting assessment approach, the solution suggests that it is economic to undertake WtE for both the OWF and DF of household wastes. At a charge of 120 €/t of collected waste, the total revenue for the optimal network is 15.02 M€/y while the profit is 5.39 M€/y. The expenses include 50.7 % for transport fuel, 29.5 % for landfill, 11.6 % for handling, 7.2 % for annualised capital investment, and 1.0 % for GHG emissions liability. The design employs a GE Reciprocating Gas Engine J-612 to generate heat and power from the OWF (biogas) and heat from incineration of the DF. With waste collection being a public service requiring no profit, the new break-even price of waste collection is 63.4 €/t, which is a 47.2 % reduction. The P-graph model selects the gas engine model with the appropriate capacity to deliver the required heat and power. The new WtE design satisfied 0.7 % of the populations heat and electricity demands. Future work will look at how to maximise the profit per capita for the WtE system design. It will also consider sensitivity and changes to GHG emissions and energy prices, population density and technologies for converting hot flue gas from incineration to heat and power.

4. Conclusions

This study successfully presented and applied a new Waste-to-Energy (WtE) targeting procedure based on the optimisation tool of P-graph. The developed model can easily be adapted to specific cases where population and waste density is sufficiently high to support residential WtE networks. For a case study of 200,000 people, the optimal targeted WtE design employed anaerobic digestion for the organic waste fraction with Combined Heat and Power using a specific reciprocating gas engine model and an incineration boiler for the dry waste fraction. With waste collection being a public service requiring no profit, the new break-even price of waste collection is 63.4 €/t, which is a 47.2 % cost reduction compared to the current cost of 120 €/t.

In future work, the introduced model should be incorporated into an overall procedure for regional network synthesis for waste processing, providing the regional targeting phase. A good candidate for a starting point of the synthesis phase model is (Tan et al., 2014), which provides a comprehensive mathematical model for all essential processing technologies. However, the future development should also add the transport into the synthesis model.

Acknowledgments

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