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Simultaneous Greenhouse Gas Reduction and Cost Optimisation of Municipal Solid Waste Management System in Malaysia

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In Malaysia, the rapid growth of population and new consumption trends are causing an increase in municipal solid waste (MSW) generation rate. To make matters worse, the current MSW handling practices in Malaysia are mostly dumping in open landfills with no proper landfill gas collection and energy recovery system, producing greenhouse gas (GHG) emissions to the atmosphere. This handling process undoubtedly causes climate change and is economically unfavourable. In this study, a multi-objective mixed-integer linear programming (MILP) approach was simulated using General Algebraic Modeling System (GAMS) to determine the optimum allocation of MSW on different disposal and treatment facilities (DTF), including sanitary landfills, incineration, recycling, anaerobic digestion, composting, and plasma arc gasification. The mathematical model utilised the augmented ε-constraint method to minimise the capital and operational cost, maximise the value of final products, and minimise GHG emissions simultaneously. As compared to the current MSW management situation in Malaysia (total cost: 7.24 M MYR/d, net GHG emissions: 70,465 t CO_2-eq/d), the least cost Pareto solution (total cost: 7.23 M MYR/d, net GHG emissions: 24,630 t CO_2-eq/d) shows a more than 65 % reduction in GHG emissions without incurring any additional cost. The 9th,10th, and 11th Pareto optimal solutions would be able to achieve the national recycling target of 22 % by 2020 as promulgated by the Malaysia Government. It is hoped that this study can provide guidance on the best allocation of MSW on DTF for decision-makers to plan and design the best in class solution for MSW management not only in Malaysia but also regions that face a similar MSW disposal dilemma.

1. Introduction

The effects of the growing population and economic development make the management of the voluminous solid waste a major challenge in many countries. The World Bank reported that the global municipal solid waste (MSW) production has reached 2.01×10^9 t in 2016 and is expected to increase by 70 % to 3.40×10^9 t in 2050 (Kaza et al., 2018). What is worse, over 90 % of the MSW did not go through a proper treatment in developing countries, which can lead to serious environmental problems like climate change, water resource pollution, and acid rain (Kaza et al., 2018). Inappropriate MSW management has squandered so much energy and generates a gargantuan amount of greenhouse gas (GHG) emissions. This leads to significant warming of the surface of the earth and other associated climate change issues within the coming decades.

As countries and industries across the world strive to reduce their carbon footprint, waste industry operations reflect a potential for carbon mitigation that is yet to be thoroughly explored. The waste industry provides a wide variety of advanced and economically viable waste management solutions and optimised programs to mitigate GHG emissions. This can be achieved by saving fossil fuel consumption from existing waste flows via efficient material and energy recovery. Through careful analysis and utilisation of different disposal and treatment facilities (DTF), many regions and cities have the opportunity to transform from a net emitter into a net reducer of GHG emissions. The selection of appropriate DTF options most often falls into the hands of local decision-makers; nevertheless, the impact of GHG emissions is not often taken into account in the part of the selection process. In Malaysia, the most commonly used MSW handling practice is open dumping landfill

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with no proper leachate collection and landfill gas collection systems, regardless the fact that recycling target has been set by the government. The low awareness on proper MSW management among Malaysian appears to be one of the main reasons of low recycling activity (The Star, 2017) despite the Malaysia Government has allocated a substantial amount of cost in MSW management (Moh, 2017). Dato' Nadzri Bin Yahaya, Malaysia's National Solid Waste Management Department Director-General, stated that 40-80 % of the expenses of the local state authority is on MSW management and public cleansing.
A few optimisation studies in MSW management had been conducted using General Algebraic Modeling System (GAMS) recently. Rizwan et al. (2018) maximised the conversion of MSW into energy and valuable products to achieve a net profit from the MSW management system in Abu Dhabi. Asefi and Lim (2017) optimised the fixed cost, transportation cost and total suitability of the MSW management system in Tehran. Lee et al. (2016) minimised the total cost of the MSW management system in Hong Kong. With the increasing attention towards climate change, it is of paramount importance that minimisation of GHG emissions should be incorporated instead of solely considering from the economic perspective. Othman et al. (2018) optimised the emission and landfill area for garden, paper and food waste using pinch analysis. Other wastes including plastic, glass, metal and economic feasibility should also be included to provide a more comprehensive result. In Malaysia, Ahmed et al. (2015) developed an optimisation model to analyse the landfill gas utilisation from environmental and economic and perspectives. Yet, the study did not consider other DTF such as anaerobic digestion and composting. Due to the great variation of treatment technology, it is essential to note that no single type of dominant DFT that is ideal for treating all types of MSW. Instead, different combinations of DFT should be explored to provide an optimised solution for sustainable MSW management. This study aims to determine the optimum allocation of different types of MSW on different DFT for MSW management in Malaysia from both GHG emissions and cost perspectives. The revenue and avoided emissions generated from different valuable products (e.g., biogas, organic fertiliser, recycled materials) are evaluated in the model.

2. Methodology

2.1 Superstructure, major assumptions, and data collection

A multi-objective mixed-integer linear programming (MILP) model was developed in this study. Figure 1 shows the superstructure representation of the model.

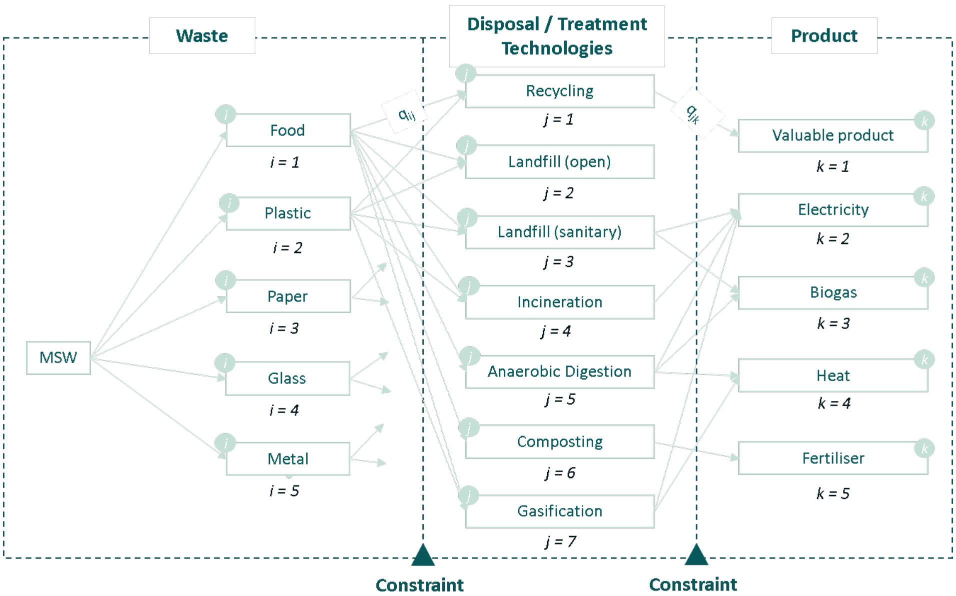

Figure 1: General superstructure of the mathematical model

Six types of DTF, namely sanitary landfills, incineration, material recycling, anaerobic digestion, composting, and plasma arc gasification, are considered to determine the best mix of MSW allocation on DTF as compared with the business-as-usual (BAU) scenario (i.e., 84.69 % of open landfill, 4.46 % of sanitary landfill, 10.5 % of recycling, and 0.35 % of waste-to-energy) in Malaysia. These DTF are considered contemporary and highly feasible to be implemented in Malaysia. Five types of MSW (i.e., food, plastic, paper, glass, and metal) are included in this model, in which they attributed to about 74 % of MSW composition in Malaysia in 2012 (JPSPN, 2013). Based on the different types of DTF and MSW, five varieties of products, namely recycled products, electricity, biogas, heat, and fertiliser, are generated in the MSW management system. The major assumptions made in the model are shown as follows.

- Constant growth rate of MSW amount by 5.19 % each year (PEMANDU, 2015);
- Constant MSW composition throughout the period and 100 % MSW source separation;
- The average round trip transportation distance of 50 km and average transportation cost of 3.5 MYR/km for all DTF. The average weight of waste collection trucks is 2.5 t. All trucks are 80 % loaded with MSW during the transportation of MSW (DANIDA, 2009);
- An operating lifespan of 20 y for all DTF.

Table 1 shows the major input data of DTF for the model, which is collected from Malaysia governmental official report to ensure the reliability of the data.

Table 1: Input data of cost components and emission factor of DTF (PEMANDU, 2015)

	Recycling	Landfill (open)	Landfill (sanitary)	Incineration	Anaerobic digestion	Composting	Gasification
Capital cost (M MYR)	230	30	114	68	60	226	650
O&M Cost (MYR/t MSW)	85	38	48	249	70	40	120
Emission factor (t CO_2-eq/t MSW)	0	1.355	0.239	0.120	0.222	0.161	0.412

2.2 MILP model development

Five constraints are included in this mathematical model as shown in Eq(1) to (7). Eq(1) emphasises that the available of i^{th} type MSW should be allocated to different DTF. Eq(2) represents the flow of component *i* in the process stream, where Eq(3) shows that the product output leaving j^{th} DTF. Eq(4) indicates the mass balance between input and output streams, while Eq(5) ensures that the total MSW received is distributed among the DTF without exceeding their capacity. Demand for renewable energy (RE) generated is described by Eq(6). It is fixed in line with the Malaysia RE target, which is 20 % in its generation mix by 2025. The total capacity of the DTF built shall not exceed the RE target to avoid excess RE supply or over investment. Eq(7) shows that the summation of heat rate and the electricity generation cannot exceed the multiplication of the lower heating value, *L*, and the waste allocated for incineration.

$$W_i \geq \sum_j q_{i,j} \times bi_{i,j} \quad (1)$$

$$in_j = \sum_i q_{i,j} \times bi_{i,j} \quad (2)$$

$$out_j = \sum_k CC_{j,k} \times \sum_k (bi_{j,k} \times q_{j,k}) \quad (3)$$

$$in_j \geq out_j \quad (4)$$

$$\sum_i q_{i,j} \leq C_j \times bi_{i,j} \quad (5)$$

$$\sum_i S_{i,j} \leq ED \quad (6)$$

$$\sum_i E_{i,j} + H_{i,j} \leq \sum_i q_{i,j} \times L \quad (7)$$

where w_i: i^{th} type waste; $q_{i,j}$: Amount of i^{th} material sent into j^{th} type DTF; $bi_{i,j}$: Binary parameter if j^{th} type DTF is selected for i^{th} type waste; in_j: Inflow of waste to j^{th} type DTF; out_j: Outflow of waste to j^{th} type DTF; $CC_{j,k}$: Conversion rate of waste in j^{th} type DTF to k^{th} product; $bi_{j,k}$: Binary parameter if k^{th} type of product can produce from j^{th} type DTF; $q_{j,k}$: Quality of k^{th} product from j^{th} DTF; C_j: Capacity of j^{th} type DTF; $S_{i,j}$: Electricity generated from j^{th} type DTF using i^{th} type waste; ED: Energy demand; Heat generated from j^{th} type DTF using i^{th} type waste; L: Lower heating value.

Eq(8) represents the first objective function in the model which highlights the total cost minimisation of the MSW management. The cost components comprise the annualised capital cost of the DTF, O&M, transportation cost of trucks, and the revenue generated from the valuable products. Details of each cost components are shown in Eq(9) to (12). Eq(13) represents the second objective function, which is the minimisation of the GHG emissions caused by MSW processing, transportation of MSW and product, and the avoided emission from the product. Details of each GHG emission of each sub-process are indicated in Eq(14) to (16). The mathematical model was programed using GAMS and solved with CPLEX solver (GAMS, 2019). The augmented ε-constraint method was utilised to ensure that both objective functions are equally important in generating a set of Pareto optimal solutions.

$$\text{Min (F)} = OPEX + CAPEX + TCOST - REV \quad (8)$$

$$OPEX = \sum_i \sum_j (UOPEX_j \times q_{i,j}) \quad (9)$$

$$CAPEX = \sum_j bi_{i,j} \times ACAPEX_j \quad (10)$$

$$TCOST = \left(\sum_i \sum_j (trans \times d_{i,j} \times q_{i,j}) + \sum_i \sum_j (trans \times d_{j,k} \times q_{j,k})\right)/tc \quad (11)$$

$$REV = \sum_j \sum_k (PRICE_k \times q_{j,k}) \quad (12)$$

$$\text{Min (F)} = EFAC + ETRANS - EAV \quad (13)$$

$$EFAC = \sum_i \sum_j q_{i,j} \times EIF_{i,j} \quad (14)$$

$$ETRANS = \left(\sum_i \sum_j (EIT_{i,j} \times d_{i,j} \times q_{i,j}) + \sum_j \sum_k (EIP_{j,k} \times q_{j,k} \times d_{j,k})\right)/tc \quad (15)$$

$$EAV = \sum_j \sum_k AV_k \times q_{j,k} \quad (16)$$

where OPEX: Operating cost of DTF; CAPEX: Capital cost of j^{th} type DTF; TCOST: Transportation cost; REV: Revenue generated from different DTF; $UOPEX_j$: Unit O&M cost of jth type DTF; ACAPEX: Annualised capital cost of j^{th} type DTF; trans: transportation cost per km; tc: Truck capacity; d: Average transportation distance; $PRICE_k$: Price of k^{th} type product; EFAC: Emission from DTF facility; ETRANS: Emission from the transportation of waste; EPRO: Emission from the transportation of product; $EIF_{i,j}$: Amount of emission owing to processing of i^{th} type waste using j^{th} type DTF; $EIT_{i,j}$: Amount of emission owing to transportation of i^{th} type waste to j^{th} type facility per km; $EIP_{i,j}$: Amount of emission transportation of k^{th} type product per km; tc: truck capacity; AV_k: Avoided emission of k^{th} type product.

3. Results and Discussions

Figure 2 illustrates a summary of the set of Pareto optimal solutions. The solutions represent the equally good alternatives with different trade-offs spreading from minimum net GHG emissions to the minimum total cost. A total of 11 Pareto optimal solutions were generated using the ε-augmented constraint method. All the Pareto optimal solutions satisfy the constraints and targets, as indicated in Eq(1) to (7). It can be seen that the total cost is increased should there is a further reduction of GHG. For example, a total treatment cost of 7.2 M MYR/d would incur 24,630 t CO_2-eq/d, while a total treatment cost of 11.03 M MYR/day would release 12,509 t CO_2-eq/d. This is mainly attributed to the fact that more diverse types of DTF are required to reduce more GHG emissions in the MSW management system.

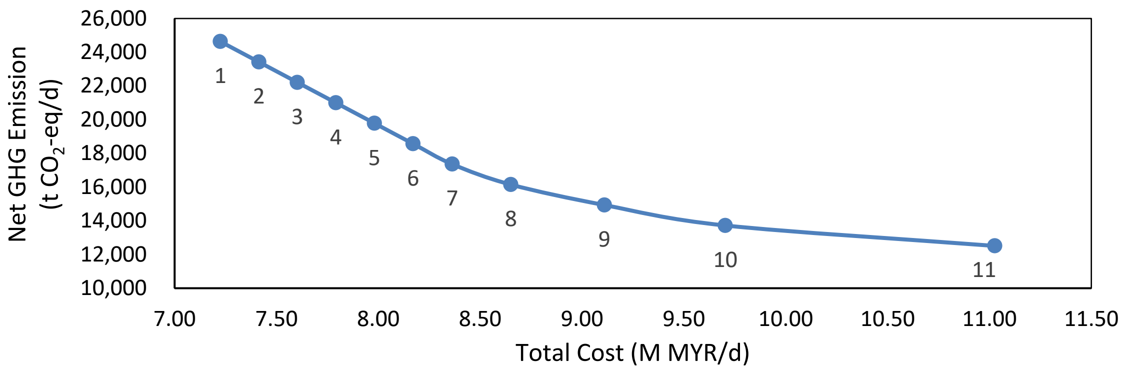

Figure 2: The Pareto frontier of Pareto optimal solutions. The number in the figure shows the number of Pareto optimal solutions, with 1^{st} indicates the least cost solution, while 11^{th} indicates the least GHG emissions solution

It is also interesting to note that the Pareto optimality changes are not consistent across the Pareto frontier. When the Pareto optimal solutions transit from the least cost solution (i.e., 1st Pareto optimal solution) to the least GHG emissions solution (11st Pareto optimal solution), the cost gap of each Pareto optimal solution increases significantly. The result demonstrates little change for the net GHG emissions when shifting from the 10th Pareto optimal solution to the 11th Pareto optimal solution (with only a net GHG emissions reduction of 9.7 %), regardless the fact that there is an increment of 12 % of the total cost. Comparing with the BAU scenario in Malaysia (total cost: 7.24 M MYR/d, net GHG emissions: 70,465 t CO_2-eq/d), the least cost Pareto solution (total cost: 7.23 M MYR/d, net GHG emissions: 24,630 t CO_2-eq/d) shows a more than 65 % reduction in GHG emissions without incurring any additional cost. When taking an average value of all the Pareto solutions (total cost: 8.45 M MYR/d, net GHG emissions: 18,569 t CO_2-eq/d) and compare with the BAU scenario, it shows a significant 74 % reduction in GHG emissions with only a 17 % increase in total cost.

Figure 3 displays the different DTF configuration of the MSW management system based on the 11 Pareto optimal solutions. The first bar on the left is the BAU scenario and the second bar (i.e., 1st Pareto optimal solution) indicates the least cost solution, the last bar (i.e., 11th Pareto optimal solution) represents the least GHG emissions solution. From 1st to 6th Pareto optimal solutions, it can be seen that open landfill with no proper leachate collection and landfill gas collection systems is still one of the alternatives to handle MSW in Malaysia. This is mainly due to less capital and O&M costs incurred in an open landfill. For the 1st Pareto optimal solution (i.e., 2nd bar in Figure 3), although open landfill constitutes around 15 % of the total MSW management system, the solution has a significant 65 % reduction of GHG emissions as compared to the BAU scenario. The open landfill is ceased to exist at the 7th solution as the Pareto optimality opts for other DTF with lower net GHG emissions.

Another prominent trend that can be observed from Figure 3 is that sanitary landfill occupies a majority percentage of around 50 % for most of the Pareto optimal solutions. This is because sanitary landfill is cheaper than other DTF such as incineration and plasma arc gasification, while at the same time manage to reduce GHG emissions due to landfill gas collection and energy recovery system (Woon and Lo, 2013). The anaerobic digestion facility accounts for around 30 % for all Pareto optimal solutions as biogas (consists of 50-70 % of methane gas) generated during the methanogenic process can be collected and recovered to generate electricity. The generated electricity from biogas can substitute electricity produced from conventional fossil-fuelled thermal power stations in Malaysia (currently run by 42 % coal and 39 % natural gas), rendering an avoided GHG emissions and creating revenue to the facility. The anaerobic digestion facility shows significant environmental and economic potential, especially dealing with organic wastes such as food waste (around 45 % of total MSW composition in Malaysia).

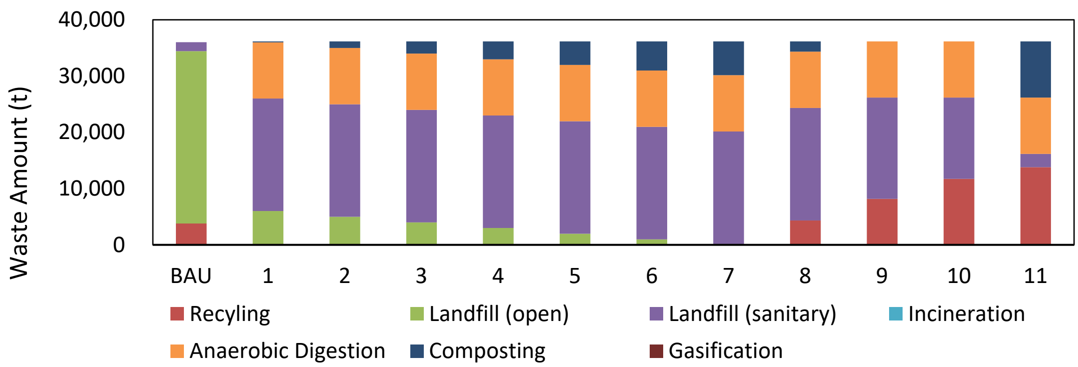

Figure 3: Configuration of the proposed MSW management system for each Pareto optimal solutions.

The percentage configuration of the composting facility shows an increasing trend from the least cost solution (i.e., 2nd bar in Figure 3) and the trend stops after the 6th Pareto optimal solution (16.6 %). Interestingly, the composting facility constitutes a percentage of 27 % for the least GHG emissions solution (i.e., 11th Pareto optimal solution) as the organic fertiliser from composting facility incurs a high avoided GHG emissions. This solution shows the highest revenue (0.47 M MYR/d) of all solutions due to the high price value of organic fertiliser (Sabki et al., 2019). Regarding the material recycling facility, its configuration percentage increases when the Pareto optimal solutions move towards the least GHG emissions solution, in which the facility occupies more than 30 % in the least GHG emission solution (i.e., 11th Pareto optimal solution). This trend suggests that material recycling facility provides a significant environmental benefit on GHG emissions during waste disposal and treatment process. Given the national recycling target of 22 % by 2020 as promulgated by the Malaysia Government, the 9th,10th, and 11th Pareto optimal solutions would be able to achieve the captioned recycling target.

4. Conclusions

The mathematical model developed in this study delivers quantitative information to the decision-makers such that high dependence on open landfills in Malaysia should be avoided and diverted to other DTF (e.g., material recycling, composting, anaerobic digestion) to reduce GHG emissions in MSW management. Among the 11 Pareto optimal solutions, it shows that an average increase of 17 % in investment can redirect MSW away from open dumping sites to valorise MSW as valuable resources such as organic fertiliser or transform to biogas for heat and electricity generation, and reducing the GHG emissions by an average of 74 %. The least cost solution shows a 65 % GHG emission reduction as compared to the current MSW management scenario in Malaysia without incurring any cost increment. It is hoped that this study can provide guidance on the best allocation of MSW allocation on DTF for decision-makers to formulate the best in class solution for MSW management. The study can also act as a reference for other places that face a MSW disposal dilemma similar to Malaysia's environmental conditions and community needs.

Acknowledgements

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