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Waste-to-Landfill Reduction: Assessment of Cost-Effective Solutions using an Optimisation Model

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Significant increases in solid waste generation and inappropriate waste management system leads to overloaded landfills, which have negative impacts on the environment and human health. Reducing waste sent to landfill has become an emerging mission in Vietnam. This study aims at assessing cost-effective solutions to reduce waste-to-landfill amount using system analysis approach. A single-objective optimisation model is formulated to minimise the cost of the system in association with different landfill waste reduction targets and values of waste separation efficiency for Hoi An city. As a result, the landfill target is directly proportional to the cost. It means the higher landfill reduction target leads to the higher cost of the system. Meanwhile, the separation efficiency is inversely proportional to the system cost. The result showed that twenty-five percent of municipal waste treated in landfills is achievable target based on the current condition of the city. Also, ten percent of municipal waste sent to landfill is an infeasible mission if the waste separation rate is too low. If waste is wholly separated at source, incineration, composting and landfill can be applied as main treatment alternatives to reduce seventy-five percent of municipal waste sent to landfill with the cost of about 1,800 USD/d.

1. Introduction

Improving waste recovery efficiency and reducing waste sent to landfill is one of the essential targets of waste management in Vietnam. However, other materials and energy recovery technologies for solid waste treatment such as incineration, anaerobic digestion or composting were not successfully applied due to a number of constraints. Besides the technical constraint, there seems to be a consensus that institutional and financial constraint are major barriers to the application of the above technologies. For instance, unachievable targets in waste initiatives were caused by lack of scientific-based policy-making and the failure of composting and incineration in some cities are results of no separation at source. Also, the efficiency of waste separated at source has impacts on the efficiency of the waste treatment system. From the economic point of view, the challenges arise from a lack of funding for incineration or bio-treatment due to high capital and operational cost, while, the waste treatment system needs to operate at a cost accepted by the majority of the community. Thus, scientific-based solutions for determining treatment technologies for possible landfill reduction target regarding the cost efficiency are required to overcome current obstacles of waste management in Vietnam.

The solid waste management is a complex system that requires an approach can handle the complexity efficiently, particular at the nexus of eco-social systems (Marshall and Farahbakhsh, 2013). The conventional approach divides the system into smaller elements, therefore, could not handle the complexity of interacting waste management system. Thus, a system approach was applied and proven that can contribute substantially to the decision making in waste management (Jeffrey, 2010). Optimisation models were developed as a system analysis tool to optimize systems in searching for an optimal solution associated with well-defined objectives, technical and managerial constraints (Chang et al., 2011). This method was widely applied to solve the economic or environmental issue in supporting scientific-based policymaking. Multi-

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objective optimisation method was applied to select the best combination of waste treatment option regards to minimising the environmental impacts like greenhouse gas (GHG) emission (Münster et al., 2015), noise (Chang and Wang, 1996) or air pollution (Galante et al., 2010) and optimising economic objectives such as maximising benefit (Harijani et al., 2017) or minimising cost (Galante et al., 2010) of municipal solid waste management (MSW). The single-objective model also has been applied to minimise waste management costs such as the tour costs and transfer visiting costs for a waste collection route (Das and Bhattacharyya, 2015), or the total cost of the entire MSW management system (Badran and El-Haggar, 2006).

Optimisation of solid waste management systems using optimisation model methodologies was lack of application in Vietnam. This study aimed at developing a single-objective model to minimise the total cost of the municipal waste management system associated with landfill reduction options of the city. Also, the impact of the waste separation rate to the system was considered in the model. The model developed helped decision-makers to identify achievable targets of landfill reduction for the city associated with the set of feasible treatment technologies as well as the waste stream management for such initiatives.

2. Material and methods

2.1 Study area and waste management status

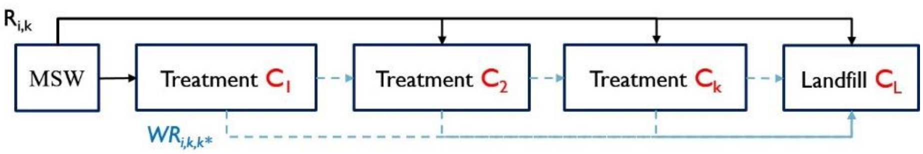
Hoi An is a city on the coast of the East Sea in the South-Central Coast region of Vietnam, located in Quang Nam Province, and recognized as a World Heritage Site by UNESCO. The city has a natural land area of 6,171.25 ha with a total population of 93,000 with unique characteristic of a tourism urban which include various types of urban such as tourist corner, urban, suburban and rural areas. The number of tourists visiting Hoi An city (HAC) has increased over the last decade, and its economy has developed tremendously.

Rapid urbanisation and tourism development in Hoi An have led to a considerable increase in municipal solid waste. Like many other cities in Vietnam, the social, economic and environmental impacts of this rising waste generation are acquiring significant attention from society. MSW generation in HAC has increased rapidly in the past few years from 24,000 t in 2011 to 29,000 t in 2015 and 30,131 t in 2016 (Pham Phu et al., 2018). Also, the tourist industry is considered one of the most dynamic industries and the most significant contributor to the economic development of the city, the implementation of sustainable MSW management, therefore, becomes more critical to secure the sustainable tourist development.

At present, HAC is the first city in Vietnam successfully carried out waste separation at source. Degradable and non-degradable waste is separated and collected on different days in a week. However, more than half of MSW in HAC (approximate) was dumped to an open-dumped landfill (Cam Ha landfill) in 2015. Other treatment facilities including a composting plant and an incinerator were not efficiently operating due to technical and market constraints, causing adverse impacts on the environmental and public health (Hoang et al., 2017b). Apparently, although there are many environmental pollution and operation problems associated with the disposal of MSW at open dumping sites, landfill might continue to be the most widely adopted practice in Hoi An in the coming years. However, one of the most significant problem in HAC currently is the overload of the current landfill. Thus, MSW of the city currently has being transported and dumped in Nui Thanh landfill, which is about 70 km far away from the city centre. Therefore, landfill reduction target has the most concern from authorities and citizens as well as local tourism sector. The city requires a scientific-based solution for long-term waste management towards landfill reduction with reasonable cost.

2.2 System model development

Authors formulate a general model, which considers all technical, economic, and environmental aspects of MSW management. The proposed model can identify the optimal waste stream and capacity of treatment facilities based on Material Flow Analysis (MFA). Figure 1 describes the waste flow of the MSW system in HAC. The type and composition of MSW were reported in another article of authors (Hoang et al., 2017a).



$R_{i,k}$: Amount of waste type i transported to treatment facility k
$Wi_{i,k,k*}$: Amount of solid residual of waste i generated by treatment facility k transported to another treatment facility k^*
C_k: The treatment capacity of treatment facility k

Figure 1: Diagram of waste material flows for modelling the MSW system

It should be noted that recycling is possible for 6 kinds of materials including paper, cardboard, plastic, plastic bags, metal and glass, those can be separately collected by informal recycling activities of scavengers and junk buyers who collect recyclable materials from treatment plants, from collection points or buying directly from households (IFR). Also, the organic material (food and garden waste) is recycled at home (HT) by feeding animals or home composting by a few households. According to Hoang et al. (2019), the total amount of waste recycled in Hoi An was about 10 % and the organic waste treated at home was approximately 5 %. The remaining fraction of MSW (after separated for recycling at home) is separated into 2 types of waste degradable and non-degradable, then collected and transported to treatment facilities including: Composting (COM), Anaerobic Digestion (AD), Incineration (INC), Incineration with electricity production (INCE) and Landfill (LF). Those were chosen as potential treatment technologies in this study. Each treatment facility generates its own residuals which need to be treated. The waste flow WR_{i,k,k^*} is the residual of material i after being processed by facility k, transported to another facility k*. For instance, residual from AD or COM facility can be incinerated, or ash from incineration is landfilled. Authors also applied input-output analysis and MFA for each treatment facility k (Figure 2). The parameter of emission from residual treatment were referenced from the model developed by Hoang et al. (2019) and emission co-efficient of material treatment process referenced from the study of Harijani et al. (2017).

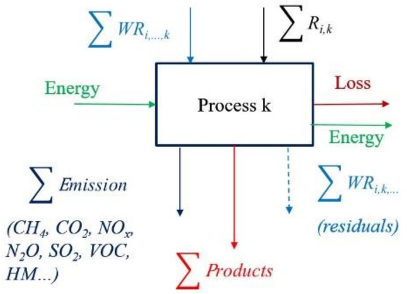


Figure 2: Input-output and material flow analysis for treatment facility k

In this study, authors considered estimating the total cost of the system including transportation cost, capital cost, variable cost and the revenue from selling recycle material and energy products (Hoang et al., 2019). The single-objective was described by Eq(1), and constraint functions were presented from Eq(2) to Eq(8):

$$Min\ Z = \sum_k \sum_i R_{i,k} \times c^{trans} + \sum_k C_k \times (c^{cap} + c^{op}) - CF \times b_{COM} - (\sum_k EP_k - \sum_k EC_k) \times b_{EN} \quad (1)$$

Subject to:

$$\sum_k R_{i,k} = W \times \alpha_i \qquad \forall i,k \quad (2)$$

$$\sum_i WR_{i,k} = \sum_{k^*}(\sum_i WR_{i,k,k^*}) \quad (3)$$

$$C_k = \sum_i R_{i,k} + \sum_i WR_{i,k^*,k} \quad (4)$$

$$C_k \leq 0.1 \times W \text{ for k = IFR} \quad (5)$$

$$C_k \leq 0.05 \times W \text{ for k = HT} \quad (6)$$

$$C_k \leq LRT \text{ for k = LF} \quad (7)$$

$$R_{i,k}, WR_{i,k,k^*}, C_k \geq 0 \quad (8)$$

c^{trans} was the unit cost of waste transportation (Ngoc, 2016) and c^{cap}, c^{os} were the unit capital cost and operational cost of the treatment plant (MOC, 2012). b_{EN} denoted the unit price for selling 1 kWh of renewable energy produced by waste treatment regulated in the decision 31/2014/QĐ-TTg on support mechanism for the development of power generation projects using solid waste and b_{COM} denoted the unit price for selling 1 t of compost product in HAC, 7 USD/t (Ngoc, 2016).

W presented the total daily MSW generated in HAC (70 t/d), and α_i were the percentage of waste fraction i of HAC (Hoang et al., 2017a). LRT denoted for landfill reduction target, shown in Table 1 and *CF, EP_k, EC_k* were the amount of compost product, amount of energy produces and consumed. Calculation of those variables was presented in other authors' studies (Hoang et al., 2019),

Parameters used in for calculation of material flows, emission coefficient of pollutants such as CH_4, CO_2, NO_x, SO_2, N_2O, VOC and heavy metal after each process from each type of waste also referenced from the study (Hoang et al., 2019).

The optimisation model was developed using the General Algebraic Modeling System (GAMS) software. Nonlinear mathematical programming and GAMS/MINOS 5.6 solver was applied to solve the model. As a result, the optimal configuration of the system can be determined, as well as the optimal flows among the various treatment facilities in the system.

2.3 Scenarios development

Three targets of landfill reduction, including 50 %, 25 % and 10 % of MSW landfilled was chosen for evaluating the system. Also, the efficiency of waste sorting at source affects significantly to system effectiveness regarding technical and economic aspects. The rate of waste separation in Hoi An was low and varied from approximately 70 to 85 % . To assess the effect of sorting waste to the system cost and pollution emission, authors chose different sorting efficiency as assumed: 70 %, 80 %, 90 % and 100 % for wholly separated. With three values for landfill reduction target (LRT) and four waste separation efficiency (SE), 12 scenarios are developed as presented in Table 1.

Table 1: Scenarios description

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12
LRT, %	50	50	50	50	25	25	25	25	10	10	10	10
SE, %	100	90	80	70	100	90	80	70	100	90	80	70

3. Result and discussion

3.1 Environmental and economic assessment

Figure 3 showed the results of minimized cost and total emission from each scenario. The results showed that the lower LRT, the higher cost for the system. With SC9-12, HAC would spend more money (from 2,100-2,500 USD/d) for waste management, while the daily expense of the city in SC1-4 was only from 1,500 USD/d to 2,000 USD/d. Also, a scenario with lower SE (SC3, SC4, SC7, SC8, SC11) resulted in the higher system cost and higher pollution emission. The blank result of SC12 meant that the model showed infeasible solution for MSW management system. In other words, the target of 10 % waste-to-landfill could not be achieved if the rate of waste separation at source was lower than 70 % for HAC.

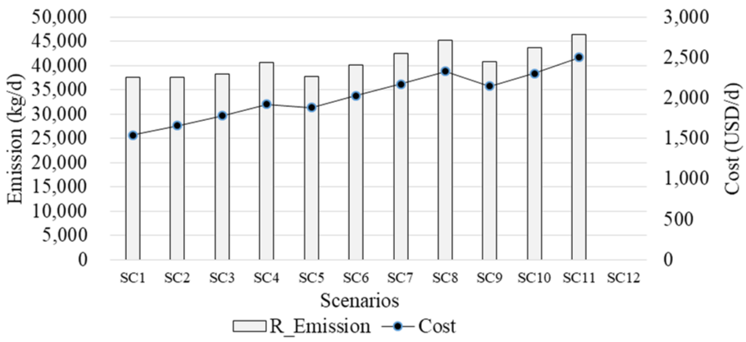


Figure 3: The cost and emission of all scenarios

Generally, technology improvement is a key factor to lower the waste management cost (Gen Li and Masui, 2018) and it is expected that spending more money will have less emission. Figure 3 showed that the total emission was proportional to the system expense. It could be explained by the treatment technologies chosen as results of the model. Scenario SC9-SC11 produced a high amount of emission (from 40-46 t/d) due to the low landfill target of 10 %, led to more waste being incinerated (Figure 5). Understandably, among waste treatment technologies, the incineration technology was well known as the most prominent CO_2 producer, which accounts for a significant proportion of emission from the solid waste management system.

The landfill was also known as a significant producer of GHG emission, including CH_4 and CO_2. Thus, when the landfill rate was high, a higher amount of GHG is emitted. Figure 4 compared the GHG emission (GWP applied for a period of 100 y) of 12 alternative scenarios. The results indicated that the scenario with a high amount of waste to landfill (50 %: SC1, SC2, SC3, SC4) produced a considerable GHG emission (about 622,000 for SC1 and 624,000 t $CO_{2\text{-eq}}$ /d for SC4). A slight increase of GHG (20,000 t $CO_{2\text{-eq}}$ /d) was caused by the increase of waste being composted and incinerated to deal with lower separation efficiency to ensure the amount of waste sent to landfill being unchanged. However, to reduce the amount of waste sent to landfill as well as the total GHG emission, composting and waste incineration technology should be applied. The result of the model indicated that composting is a preferred technology for Hoi An city due to its low cost and low emission factors. However, facilities should be medium scale to possibly obtain profits (Mirza et al., 2018).

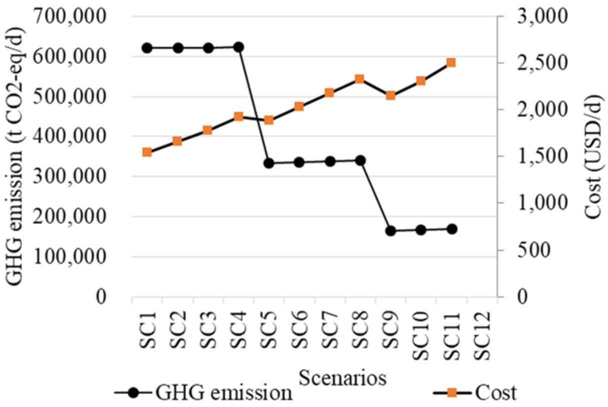


Figure 4: GHG emission of alternative Scenarios

3.2 Potential waste management scenario

If MSW in HAC could be entirely separated at source (SE=100 %), the percentage of waste sent to landfill could be reduced to 10 % with a cost of about 2,100 USD/d. However, 100 % of waste separated at source seems to be impossible for a Vietnamese city like HAC, the SC10, then, is more applicable for HAC with 10 % of MSW sent to landfill policy. It will cost about 2,350 USD/d for waste management. Consequently, a composting plant with a capacity of about 32 t/d and an incinerator of 28 t/d capacity was proposed associated with other informal recycling activities.

The LRT of 25 % appeared as a reliable target in regarding economic as well as environmental aspects. However, if the MSW SE was about 80 % (SC7), the amount of money spend and total emission per day would be about 2,200 USD and 43 t. It was almost identical to the cost and emission of SC9, which had only 10 % of MSW sent to landfill. Thus, a substantial reduction in cost needed a higher SE, such as 90 % (SC6) or 100 % (SC5). Since it was infeasible to have MSW separated utterly (100 %), SC6 was more feasible to achieve with 25 % waste-to-landfill. Thus, a 32 t/d composting facility and a 17 t/d incinerator were proposed treatment practices with a total daily cost of 2,000 USD/d, as results of the model.

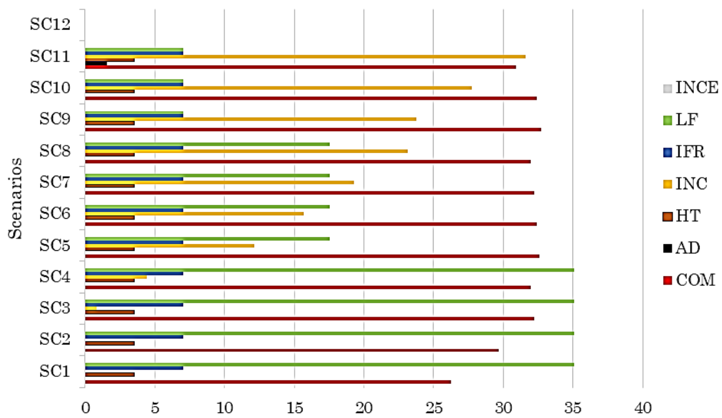


Figure 5: Treatment options and capacity (t/d) for 12 scenarios

4. Conclusion

The optimization model helped the authority to evaluate the options for landfill reduction implementation in HAC. The results of the study showed that composting and incineration are favoured treatment technologies toward landfill reduction in HAC. However, it also indicated that the waste separation efficiency should be 90 % or higher achieve economic and environmental goals solution for landfill reduction. With 90 % of waste separated, HAC could achieve the target of 10 % and 25 % of MSW sent to landfill with a daily cost of 2,350 USD/d and 2,000 USD/d. The incineration was a valuable treatment alternative for waste-to-landfill and GHG emission reduction. However, in term of the total amount of pollution emission, incineration was not favoured due to a high emission factor of CO_2. Composting appeared as a suitable treatment technology for degradable waste in HAC due to the low cost and low emission factors.

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