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Optimal process network for municipal solid waste management in Iskandar Malaysia

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ABSTRACT

Ineffective management of municipal solid waste (MSW) may cause degradation of valuable land resources and create long-term environmental and human health problems. A sustainable and efficient waste management strategy is needed to balance the need for development, the quality of human life and the environment. This study aims to synthesis a MSW processing network to produce energy and value-added products for achieving economic and environmental competitiveness. An optimisation model that integrates four major utilisation technologies was incorporated to facilitate a cost-effective processing network. The model is able to predict the best mix of waste treatment technologies, forecast the production of by-product from waste treatment process, estimate the facility capacity, forecast the greenhouse gas (GHG) emission of the system, and eventually generate an optimal cost-effective solution for municipal solid waste management (MSWM). Four scenarios for MSWM were considered to analyse the economic impact of different waste utilisation alternatives: i) the business as usual (BAU) scenario as a baseline study, ii) the waste-to-energy (WTE) scenario, iii) the waste-to-recycling (WTR) scenario, and iv) the mixed technology (MIXTECH) scenario. The MIXTECH scenario was able to provide the best mix of waste utilisation technologies. The optimal waste allocation in terms of percentage involved landfill gas recovery system (LFGRS) (14%), mass burn incineration (3%), material recycling facilities (MRF) (56%), and composting (27%). The optimal scenario would be able to achieve the renewable energy (RE) target, achieve the recycling target and promote composting as the waste reduction alternative for the region being studied. Sensitivity analyses were conducted for the optimal or MIXTECH scenario to examine the effect of the RE target and GHG emission reduction target with respect to the system cost and waste allocation to each technology. The proposed mixed integer linear programming (MILP) model was applied for Iskandar Malaysia (IM) as a case study.

1. Introduction

Municipal solid waste (MSW) refers to waste generated from residential, commercial, institution and public parks (Fodor and Klemeš, 2012). Solid waste management (SWM) involves many technologies associated with controlling waste generation, handling and storage, transportation, processing and final disposal. The hierarchy of SWM was formed since 1970s, several evolution, different versions of solid waste treatment hierarchies exist. One of those affordable hierarchies is suggested by Finnveden et al. (2005), in the order of reduction of waste amount, reuse, recycle, compost or recovery through incineration and finally landfill disposal. It explained that the main objective of SWM is to treat the waste generated. In addition, energy and recyclable material can be recovered as by-products to achieve sustainable waste management that is environmental friendly, economically reasonable and socially acceptable (Tchobanoglous and Kreith, 2002).

Rapid urbanisation, population growth and industrialisation contribute towards large-scale increase of MSW in Malaysia. These factors have changed the characteristics and composition of the solid waste generated. The daily waste generation has also shown an upward trend. Waste generation was 16,200 t in year 2001. This amount increased to 19,100 t in 2005, 17,000 t in 2007 and 21,000 t in 2009 (Ahmad et al., 2011). Due to the increased population growth rate, the daily solid waste generated is estimated to be 31,000 t/d by 2020 (Johari et al., 2012).

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Depending on its characteristics, the MSW can be preferentially processed by different approaches. The present waste management methods in Malaysia are highly dependent on landfill as only 5.5% of the MSW is recycled and 1% is composted, while the remaining 94.5% of MSW is disposed on the landfill site (Periathamby et al., 2009). The practice of waste segregation is random and unofficial in Malaysia. Waste recycling is mainly performed by garbage scavengers at the landfill sites. To date, SWM in Malaysia is at the stage of transition and planning towards sustainable and effective approaches. Ineffective management of waste may cause degradation of valuable land resources, increase land costs, and create long-term environmental and human health problems. Sustainable and more efficient waste management strategies are needed to reduce the heavy reliance on landfills. Malaysia aims to establish a holistic framework that considers the trade-off involved in the segregation process and the economic performance of different MSW practices to achieve the national MSW recycling rate (22% of the total MSW) by the year 2020 (Ministry of Housing and Local Government, 2005). The segregation and recycling of waste are essential to improve the performance of waste processing.

1.1. Literature review on waste management model

The complexity of SWM includes the prediction of solid waste generation, selection of waste treatment technologies, selection of facility sites, estimation of facility capacity, operation of the facility, scheduling of the system and transportation of the waste. SWM can be modelled through a system perspective (Seadon, 2010). System analysis tools for supporting decision making in waste management were developed since 1970s, these models can be categorised into two groups: (1) system engineering (SE) models and (2) system assessment (SA) models (Pires et al., 2011). The SA models can be used to analyse the performance of an existing waste management system, for example life-cycle assessment (LCA), risk assessment, and material flow analyses (Juul et al., 2013). For instance, Chen and Chang (2010) developed a range of SA models to assess the performance of MSW recycling in Taiwan. The models included the diffusion effect and the organisational learning effect as the key variable for recycling performance, however, other variables such as costing and environmental protection are not considered in the models. The LCA tool is a popular tool to solve the complex issues of SWM. For instance, Othman et al. (2013) reviewed the application of LCA for the assessment of integrated solid waste management for several Asian countries. The study focused on the assessment of environmental impacts of various waste treatment technologies and concluded that recycling, anaerobic digestion and thermal treatments are effective technologies for the Asian countries. Wanichpongpan and Gheewala (2007) used LCA as a decision tool to assess the environmental impact of landfill gas-to-energy system in Thailand, they concluded that a centralised landfilling facility is environmental and economical beneficial as compared to small landfills. Poeschl et al. (2012a, b) used LCA to analyse the biogas production system and utilisation pathways from different input sources including from MSW and feedstock. Liamsanguan and Gheewala (2008) used LCA to assess the holistic impact of integrated solid waste management towards the mitigation of greenhouse gases emission in Phuket, Thailand. These LCA studies tend to assess the waste treatment technologies focussing on the environmental impact and with less consideration on the detailed modelling and optimisation for the economical impact of the processes. While SA models focus on the assessment and analysis of the existing systems, SE models focus on the design and solution of a waste management system. Methods such as multi-criteria decision models (MCDM), simulation models, forecasting models, cost-benefit analysis, and optimisation models are widely used in the SE approach (Pires et al., 2011). The optimisation model developed using SE model emphasises the design of a system by a specific objective function which gives the best solution to the objective function (Juul et al., 2013). Various types of techniques have been implemented as an optimisation model for SWM. These include the linear programming (LP), mixed integer linear programming (MILP), non-linear programming (NLP), multi-objective programming (MOP), stochastic programming, two-stage programming, fuzzy method programming, and hybrid models. An overview of the optimisation models for SWM are summarised in Table 1.

The early stage of SE model developed for SWM focused on the cost-effectiveness principle of LP with a single-objective optimisation scheme (Juul et al., 2013). For example, Münster and Meibom (2010, 2011) designed an energy system using the Balmorel model to optimise the investment cost for different waste-to-energy (WTE) technologies in the northern Europe. In addition, a LP model was developed by Rathi (2007) to investigate the SWM technologies that focused on composting by taking into account both the economic and environmental impacts. Other LP model as developed by Salvia et al. (2002) also addressed the similar issue of waste management and emphasised on the analysis of one particular technology. LP model is typically applied and limited to a single process that does not support the evaluation and selection of multiple technologies. More powerful modelling tools are needed to conduct modelling work for SWM notably for the real case studies that involve a range of uncertainties. For instance, more complex modelling methods including mixed integer linear programming (MILP), non-linear programming (NLP) (Chang et al., 1997; Shadiya et al., 2012), stochastic programming (Guo and Huang, 2009b), fuzzy logic (Yeh and Xu, 2013) and hybrid model (Xu et al., 2010; Li and Chen, 2011; Chang et al., 2012) were developed to assess the complex scenarios of SWM in the real world. MILP is relatively simple and can be applied to consider the complex scenario with uncertainties using the binary selection function that facilitates the selection of multiple technologies and dynamic planning of resource network for SWM. Badran and El-Haggar (2006) proposed a MILP model for the optimal management of MSW at Port Said, Egypt, with the objective of minimising the waste collection and transportation costs. Dai et al. (2011) designed a MILP model to assess waste allocation issue and the expansion of capacity for the waste treatment facility. Santibañez-Aguilar et al. (2013) determined the optimal supply chain network for waste utilisation using MILP. Ng et al. (2013) developed a MILP model to determine the waste-to-energy network that optimised the cost, waste energy potential utilisation, and the carbon footprint.

As presented in Table 1, many models were developed based on various waste management technologies including composting, recycling and disposal to optimise the economical factor. Relatively fewer models have simultaneously considered the economical factor based on energy system and WTE technologies such as that by Münster and Meibom (2011). Ng et al. (2013) developed a WTE processing network with integrated consideration for economical and environmental factor. However, the model did not incorporate other waste treatment alternatives such as recycling or composting. As a whole, it is of great challenge and interest to integrate both the waste management system and energy system into the modelling works to achieve optimal economical and environmental consideration.

1.2. Research objectives and scopes

In general, MSW in Malaysia is typically disposed in a bin or container within the house premise and collected by the respective