CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863025

Carbon Emission and Landfill Footprint Constrained for Waste Management using Cascade Analysis

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An effective approach to handle overwhelmed generation of municipal solid waste (MSW) by waste diversion from landfill is envisaged in promoting the utilisation of the alternative options, such as recycling and waste to energy (WtE). As different waste components of the MSW account for the different landfill footprint as well as the emission impact, an effective landfilling practice can satisfy the target demand, while optimising the capacity of the landfill. A new numerical method of pinch analysis is applied for identifying the minimum capacity of total non-biodegradable (TnB) waste accepted in the landfill and the amount of biodegradable waste to be diverted from landfill. The algebraic technique of cascade analysis is performed to execute a systematic approach to sustainable landfilling practice for waste management. Based on the findings, the minimum area of TnB to allocate in the landfill is 4,027 m^2 and 25,654 t of food waste is needed to be diverted from landfill. Waste Management Pinch Analysis (WAMPA) is then further applied to identify the optimal waste management strategy of the diverted waste. A hypothetical case study is provided to illustrate the technique.

1. Introduction

Landfilling remains the predominant approach to dispose municipal solid waste (MSW), regardless being the lowest preferences in the waste management hierarchy and an inverse approach to achieve sustainable environmental development. Dependency on this method has resulted in the exhaustion of the landfill capacity earlier than anticipated besides confronting with the immense burden of the adverse environmental impacts, particularly the contribution of total greenhouse gas (GHG) emission consists of methane (CH_4) and carbon dioxide (CO_2). As an integrated waste management concept comprises landfilling as a method to dispose of waste, an imperative approach of landfill management through waste diversion is envisaged to tackle the dwindling issue of the landfill space, align to the effort on minimising the emission impact from landfill (Pariatamby, 2014). To address the problems, an optimal approach to allocate different waste component in the landfill using a numerical method of landfill cascade is proposed in this work. The technique is able to identify the minimum capacity of total non-biodegradable (TnB) waste and the diversion of the biodegradable component by incorporating with the landfill reduction and emission constraint. In other words, the technique is applied to account the amount of biodegradable waste to be diverted to other alternative options such as reuse, reduce, recycle (3R) and waste to energy (WtE) based on Pinch Analysis principle.
Pinch Analysis has been extensively used as a tool for optimisation in chemical process and integration. It was developed based on thermodynamic principles and its basic concept is to match with the available internal heat supply and appropriate heat sinks for energy efficiency (Klemeš and Kravanja, 2013). It has been further applied in a number of fields, including Total Site Heat Integration (Klemeš et al., 1997), Mass Exchange Network (El-Halwagi and Manousiouthakis, 1990), Water Network Synthesis (Foo, 2009), Hydrogen pinch (Fonseca et al., 2008), Power Pinch (Alwi et al., 2012) and Mass Pinch for biorefinery (Martinez-Hernandez et al., 2013). As for emission targeting, Linnhoff and Dhole (1993) investigated the total site concept for saving fuel and power in industrial facilities. Tan and Foo (2007) continued the work by proposing a new technique by targeting the zero-carbon energy sources known as Carbon Emission Pinch Analysis (CEPA) for the emission

Please cite this article as: Khairunnisa Izzati Othman, Jeng Shiun Lim, Wai Shin Ho, Haslenda Hashim, Ainur Munirah Hafizan, 2018, Carbon emission and landfill footprint constrained for waste management using cascade analysis, Chemical Engineering Transactions, 63, 145-150 DOI:10.3303/CET1863025

constraint of regional energy planning using a graphical presentation. The work is then improved and extended using a numerical method of cascade technique with emissions and land availability constraint of the energy sources (Foo et al., 2008). In another study, Othman et al. (2017a) introduced a numerical gas system cascade analysis for the optimal biogas storage system. Further development of pinch analysis related to waste management strategy, known as WAMPA has been formulated by Ho et al. (2015) and the feasibility was then further addressed to provide clear insight of the reduction for each waste component (Ho et al., 2016). WAMPA requires users to identify the carbon emission constraint with targeted landfill reduction and adjust to waste management options including 3R, WtE, and landfilling. This early work was restricted to the unidentified technique of the landfill reduction, which is steered to the diversion strategy from the landfill. Othman et al. (2017b) reduced the gap by proposing a diversion technique using a graphical method of pinch analysis. The graphical approach limited to the visual representation and accuracy of the findings. The algebraic targeting approach of cascade analysis is presented in this work with aims to satisfy the emission and landfill constrained for the optimal solution of landfilling practice and the implementation of diversion strategy.

2. Problem statement

Landfill encompasses waste that can be decomposed by the microorganism known as biodegradable waste (i.e. food waste, yard waste, paper) and non-biodegradable waste (i.e. plastic, glass, metal) which accumulated as the sources (S_i) of the landfill capacity. As the large volume of non-biodegradable waste damages the environment besides polluting the soil (Bharadwaj et al., 2015), thus, finding the minimum capacity area of this waste component of the reduced landfill space will stimulate the favour options towards recycling activities as they are potentially being a recyclable material. Meanwhile, to achieve the targeted emission constraint, the excess capacity of biodegradable waste will be diverted as illustrated in Figure 1. The problem definition of landfill constrained for waste management planning is stated as follows:

- Given a landfill demand of an area and at the same time restricted to a maximum emission level $E_{Dj.}$ Dividing the emission limit by the targeted area demand yield the emission factor of the targeted area demand.
- Given a set of the projected waste component as a source = {i|I = 1, 2, 3, …, $N_{sources}$} to be accommodated in a targeted landfill area (Figure 1). Note that, each waste sources (i.e. yard waste, paper, food waste) have different waste density and compaction rate, which contributed to the different landfill footprint of $S_{i,}$ and characterised by the new emission factor E_{Si} (t CO_2/m^2) of each component through the conversion of area and emission per weight unit (t CO_2/t). Taking these revised values into account, as area (m^2) is the demand in the unit of acquire, the conversion unit is the necessary step to calculate before proceeding to cascade analysis.

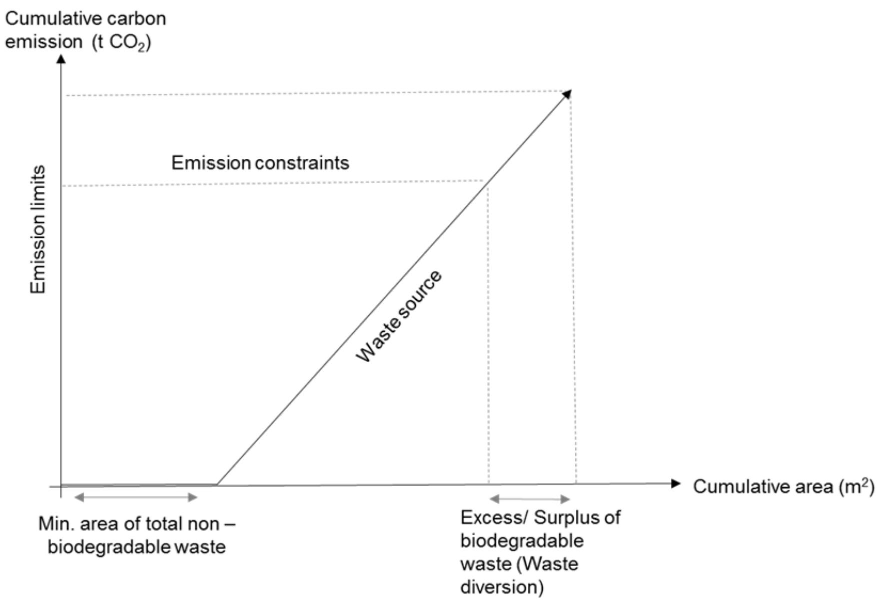

Figure 1: Landfill planning composite curves for minimum area of total non-biodegradable waste

3. Methodology

A cascade analysis tool for energy planning which invented to determine the minimum zero and low carbon sources (Foo et al., 2008) are adopted in this work by targeting the minimum landfill capacity of TnB waste sources with emission and landfill constrained. Table 1 shows the initial data for the hypothetical case study. For the simplicity, non-biodegradable waste sources are lumped together as the single category. To identify the landfill area footprint, the waste generation is converted to landfill area footprint as for the landfill capacity (Othman et al., 2017b). It is assumed that the height for both landfills are 10 m with well-compacted and normal compaction rate in Landfill 1 and 2. To demonstrate the approach the calculated data of Table 2 is used to conduct the landfill cascade.

Table 1: Initial data for hypothetical case study of landfill cascade in the year 2020

Biodegradable waste	Emission intensity ($t\ CO_2$)	Waste density (t/m^3)	Compaction rate		Projected waste generation (t) Year 2020	
			Well compacted	Normal compaction	Landfill 1	Landfill 2
Garden waste, G	0.21	0.092	0.20	0.25	5,000	3,000
Paper, Pp	0.58	0.152	0.15	0.20	45,000	70,000
Food waste, Fw	0.45	0.514	0.33	0.35	120,000	20,000

Table 2: Hypothetical data to conduct landfill cascade in the year 2020

Biodegradable waste	Landfill 1		Landfill 2		Total emission limits ($t\ CO_2$)	Targeted landfill area demand (m^2)
	Expected Land Footprint (m^2)	Emission factor ($t\ CO_2/m^2$)	Expected Land Footprint (m^2)	Emission factor ($t\ CO_2/m^2$)		
Garden waste, G	652	0.97	1,359	0.77	120,000	27,000
Paper, Pp	6,908	5.88	5,921	4.41		
Food waste, Fw	7,704	7.01	1,362	6.61		

The objective of this work is to determine the minimum area for TnB waste needed to accommodate in targeted landfill area demand and identify the surplus of the biodegradable waste with the emission constraint. The following steps are conducted to perform the cascade analysis adopted from the previous work of carbon-constrained energy planning (Foo et al., 2008) which shown in Table 3 and Table 4 and described below:

- The levels of emission factor (E_k) of waste sources are arranged in ascending order in the 1st column. Further, entries in column 2 ($E_{k+1} - E_k$) are used to represent the emission increment between successive rows of Column 1.
- In column 3 and 4, the demand of landfill area (D_j) and the expected of landfill footprint of waste sources (S_i) are in place at their respective level of emission factor, k.
- Entries in column 5 are then computed as to provide the net surplus or deficit of landfill footprint (L_c), obtained via the net between the area demands and projected area of waste sources at each ($\sum S_i$ - $\sum D_j$). A positive value indicates the surplus and the negative value indicates a deficit.
- The cumulative of net landfill footprint surplus/ deficit is calculated down the different level of E_k to yield the cumulative area cascade in column 6 with assuming zero for the projected waste landfill footprint of non-biodegradable waste. The negatives value depicted in the column indicated that the area of waste sources is insufficient in supplying the waste component to be accommodated in the landfill. This may be confirmed by inspection of the data in Table 1, without considering the TnB waste source. (It is calculated that total of projected landfill area for biodegradable waste is 24,620 m^2 versus total landfill area demand of 27,000 m^2).
- The subsequent step is to determine the carbon emission (CO_2) load which resulting the assumed amount of non-biodegradable area sources. The emission load at each E_k (ΔA_k) is obtained from the cumulative area surplus or deficit and the emission factor difference across two successive level. Cascading the CO_2 load down the E_k level of column 8 yields the cumulative CO_2 load. A feasible cascade characterises by non-negative values of cumulative A_k in column 8 where CO_2 limit is not exceeded. As such Table 3 is infeasible cascade due to its negative value of cumulative A_k.

- In column 9, an interval of TnB landfill area source is calculated by dividing cumulative A_k by the difference between the emission factor at level k and the non-biodegradable waste sources.
- To have non-negative values of the cumulative CO_2 load in column 8, the absolute value of the largest negative A_{CS} will then be used as the area of TnB waste sources in landfill area cascade (Table 4). The magnitude of the minimum A_{CS} represents the minimum TnB area demand (L_{CS}) of the landfill footprint system while the final row in column 6 in Table 4 represent the surplus area (L_{ES}) or waste diversion from the waste component which has the highest emission per area.

Table 3: Infeasible landfill cascade

Emission factor (E_k)	Emission change (ΔE_k)	Area demand ($\sum D_j$)	Waste sources in area ($\sum S_i$)	Net landfill footprint ($\sum S_i - \sum D_j$)	Surplus/ Deficit area (L_C)	Yield of deficit/ surplus area ($\Delta A_k = L_C \Delta E_k$)	Cumulative yield deficit/ area (ΠA_k)	Interval landfill sources ($A_{CS,k}$)
0								
	0.77							
0.77			1,359	1,359				1,359
	0.20				1,359	272		
0.97			652	652			272	652
	3.44				2,011	6,918	-	
4.41			5,921	5,921			7,190	5,921
	0.03				7,932	238	-	
4.44		27,000		(27,000)			7,428	
	1.44				(19,068)	(27,458)	-	
5.88			6,908	6,908			(20,030)	6,908
	0.73				(12,160)	(8,877)	-	
6.61			1,362	1,362			(28,907)	1,362
	0.40				(10,798)	(4,319)	-	
7.01			7,704	7,704			(33,226)	7,704
					(3,094)	-	-	

Table 4: Feasible landfill cascade

Emission factor (E_k)	Emission change (ΔE_k)	Area demand ($\sum D_j$)	Waste sources in area ($\sum S_i$)	Net landfill footprint ($\sum S_i - \sum Dj$)	Surplus/Deficit area (L_C)	Yield of deficit/ surplus area ($\Delta A_k = L_C \Delta C_k$)	Cumulative yield deficit/ area (ΠA_k)
					L_{CS}: 4,740		
0							
	0.77				4,740	3,650	
0.77			1,359	1,359			3,650
	0.20				6,099	1,220	
0.97			652	652			4,869
	3.44				6,751	23,223	
4.41			5,921	5,921			28,092
	0.03				12,672	380	
4.44		27,000		(27,000)			28,473
	1.44				(14,328)	(20,633)	
5.88			6,908	6,908			7,840
	0.73				(7,420)	(5,417)	
6.61			1,362	1,362			2,423
	0.40				(6,058)	(2,423)	
7.01			7,704	7,704		-	0 .00
					L_{ES}:1,646	-	(Pinch Point)

The minimum capacity of TnB and waste diversion is performed in the cascade technique to satisfy the emission and landfill constraint. The diversion techniques involved the reduction of the highest emission per area landfill of the biodegradable waste component. As there is an emission limit for landfills and for achieving sustainable landfilling practice, removing the highest emission per area of waste will obtain the possible lowest landfill emission of CO_2.

4. Result and Discussion

Based on Table 4 (feasible landfill cascade), the minimum of TnB waste sources in the landfill is needed as 4,740 m^2 while an excess area or diversion of 1,646 m^2 or 25,642 t from food waste in Landfill 1 (well compacted) is observed due to the emission limit is reached. In this case study, it is noted that the individual emission limits of each landfill are disregarded with only the total CO_2 emissions and landfill area are being of concern to the planners in this study. When the overall demand is specified, emission limits of the excess in one landfill can be offset when another landfill generates below its corresponding limit. Low emission limit will compensate to other higher one. The pinch point of this problem is located as 7.01 t CO_2/m^2. As the total landfill area is reduced and the diverted waste from the food waste portion is identified in Landfill 1, consequently WAMPA is conducted which depicted in Figure 2. As to conduct WAMPA, the additional hypothetical data as shown in Table 5 is shown below.

Table 5: Additional data to conduct WAMPA

	Waste generation in year 2017		GHG emission reduction target (%)	General emission for WtE (t CO_2/t)
Food waste (t)	WTE (t)	Landfill (t)		
	40,000	130,000	5	0.28

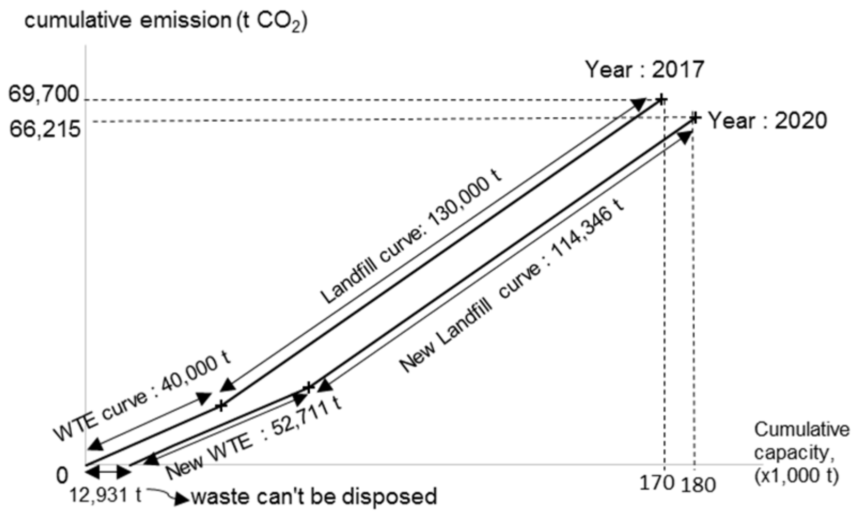

Figure 2: WAMPA for food waste

It is suggested to meet up to 9,066 m^2 (114,346 t) of reduced landfill footprint of food waste incorporated with 5 % carbon emission reduction in total food waste system, an additional of 12,711 t in the capacity of WtE technology has to be implemented as depicted in Figure 2. 12,931 t of food waste cannot be disposed of as it is reaching the emission limit. An adjustment is therefore required for ensuring all the waste is sustainably disposed such as the food waste needs to be recycled to animal feed or increasing the allowance for GHG.

5. Conclusion

Algebraic pinch analysis of landfill area for waste management planning has been presented in this work. The findings of minimum 4,740 m^2 area of TnB in the landfill and 25,642 t of food waste need to be diverted from landfill is identified from this approach. The newly developed framework is based on Pinch Analysis which has been used in the various application and now has been extended to landfill management and integrated with WAMPA which is able to identify the optimal waste management strategy. The cascade technique of landfill provides precise values than the previous works of the graphical methods. However, this technique can only be used for cases wherein the individual emission and total area is disregarded.

Acknowledgments

The author would like to acknowledge the financial support in the form of research grant by UTM with grant no.Q.J130000.2446.03G62.

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