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Future Assessment of Municipal Solid Waste Management Strategy for Taichung Special Municipality in Taiwan

Yao-Jen Chang, Shuang-Fu Yeh and Min-Der Lin*

***Abstract*—Efficient treatment of municipal solid waste (MSW) is an important subject for urban planning. Recently, the incineration has become the major MSW treatment policy in Taiwan. However, due to the high material recovery rate, the incinerators faced problems that there is not enough MSW available for treatment. For Taichung City and Taichung County, the total daily generation of MSW is 1,483 ton/day which is less than the total treatment capacity of 2,220 ton/day of the existing three incinerators. Therefore, the incinerators turn to incinerate general industrial wastes in order to operate at a suitable condition. Moreover, since there is no regional MSW management program between Taichung City and Taichung County, the economies of scale can be hardly achieved. Owing to the Taichung City and Taichung County are about to merge into a Taichung Special Municipality, it is a good opportunity to develop regionalized MSW treatment strategies for the new metropolitan. This study employed mixed integer linear programming to evaluate the least-cost MSW treatment strategies for Taichung Special Municipality under different scenarios. The total number of 29 districts, 3 incinerators and 16 landfills, associated with the real world operation data, were considered in the optimization models to make the results more practical.**

***Index Terms*—municipal solid waste, Taichung City, mixed integer linear programming, optimization**

I. Introduction

Efficient treatment of municipal solid waste (MSW) is an important issue for urban planning. Recently, incineration has become the major MSW treatment policy in Taiwan. But due to the high material recovery rate, the incinerators faced problems that there is not enough MSW available for treatment. Taichung City and Taichung County will merge into a Taichung Special Municipality in 2011, therefore MSW management (MSWM) strategies for Taichung Special Municipality should be reviewed and re-planned. For example, material recovery of MSW will still be a major MSWM policy, but the existing material recovery facilities (MRF) in Taichung City and Taichung County have not achieved the economies of scale yet. Therefore, it is a good opportunity to develop a regionalized MSW treatment strategy and determine suitable number and sites of MRF and landfills for the Taichung Special Municipality.

Over the past 10 years, several studies have utilized different mathematical programming techniques, such as linear programming (LP)[1-3] and mixed integer linear programming (MILP)[4-9], to investigate MSWM problems. Due to the involvement of multi-municipality and multi-facility issues, regionalization of MSWM program becomes more complicated, and the development of an effective analytical tool will be helpful for decision makers.

This paper employed MILP techniques to establish a MSWM optimization model that is capable of solving multi-municipality and multi-facility MSWM problems. Furthermore, a case study of Taichung Special Municipality will also be investigated. The optimal strategies obtained by realistic operation parameters will be presented to determine the suitable number and sites of MRFs and landfills of the regionalization of MSWM program.

II. Case Study: Taichung Special Municipality

The Taichung Special Municipality is located in middle Taiwan. The area is composed of 29 administrative districts. Currently, there are 3 incinerators and 16 landfills, as shown in Fig.1. However, there has no large-scale MRF, so determining suitable MRF sites and capacities is an important subject for Taichung Special Municipality.

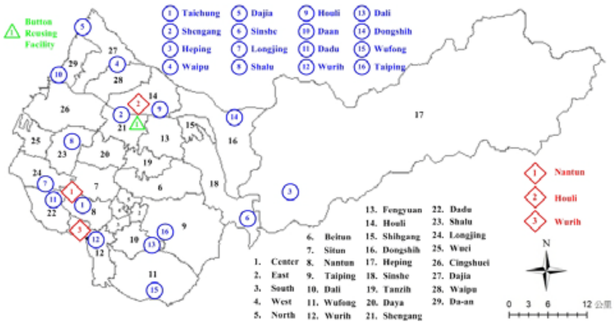

Fig.1 Locations of the incinerators, landfills and districts in the Taichung Special Municipality

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The daily MSW generation is approximately 2,478 tons in Taichung Special Municipality. The average ratios of waste, recycled resources and food waste are about 63%, 28% and 9%, respectively [10]. The composites of resource cycling and food waste are shown in Fig.2 (a) and (b), respectively.

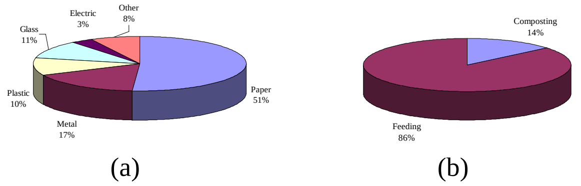

Fig.2 Composites of resource cycling and food waste [10]

The MSW treatment costs for the 3 incinerators, namely Nantun, Houli and Wurih, are 489, 339 and 129 NT$/ton, respectively, and the treatment cost of general industrial waste is 2,100 NT$/ton for each incinerator. Additionally, according to the contracts between the incinerators and government, the guaranteed MSW quantity supplied by government is 603, 553 and 510 ton/day, respectively [10]. The waste to electricity transfer coefficient (WETC), the selling rate of electricity (SRE), the selling prices (SP), the generated rate of button ashes (GRBA), the generated rate of fly ashes (GRFA) and loading of the 3 incinerators are shown in table 1.

Table 1 The operation parameters of incinerators

Incinerator	WETC (KWh/ton)	SRE (%)	SP (NT$/KWh)	GRBA (%)	GRFA (%)	Loading (%)
Nantun	407	76	1.50	16	3	71
Houli	569	82	1.45	18	5	85
Wurih	584	79	1.58	15	6	91

Source: Taiwan environment data warehouse, Environmental Protection Administration: Taiwan, Republic of China.

For each new MRF, the treatment cost of recycled resources and food waste is 1000NT$/ton. The benefits of recycled resources and food waste are 2,280 and 2,094 (NT$/ton), as calculated in (1) and (2), respectively**.** The ratios and selling prices of recycled resources and food wastes are shown in Table 2 and Table 3, respectively.

$$RP = 0.51*1000+0.17*2000+0.1*4000+0.11*8000+0.3*5000 = 2280 \qquad (1)$$

$$CP = 12{,}500*0.14+400*0.8694 = 2094 \qquad (2)$$

where *RP* and *CP* is the unit price of resource cycling and food waste reused.

Table 2 The ratio and selling price of recycled resources

Term	Paper	Metal	Plastic	Glass	Electric	Other
Ratio [1](%)	51	17	10	11	3	8
Price [2](NT$/ton)	1,000	2,000	4,000	8,000	5,000	-

Table 3 The ratio and selling price of food wastes

Term	Composting	Feeding
Ratio [1](%)	14	86
Price [2](NT$/ton)	12,500	400

For each landfill, the treatment cost of the general industrial waste, button ash and fly ash are 2,100, 2,100 and 6,000 NT$/ton, respectively, and maximum capacity of landfill is 100 ton/day. For button ash reusing, the treatment cost is 1,500 NT$/ton, and there is no capacity limit for button ash reusing facility.

III. Optimization Model

The optimization model developed in this study aims at analyzing the most economical strategies for the waste stream allocation of MSWM problems. The framework of MSWM is shown in Fig.3.

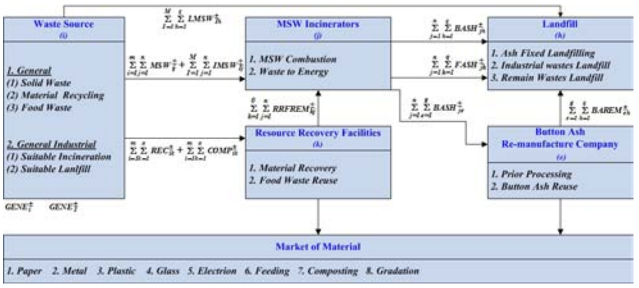

Fig.3 The framework of MSWM

The objective function is to minimize total net cost of MSWM, which is the summation of transportation cost and treatment cost minus electric revenue, as shown in Eq. (3):

$$\textit{Minimize } COST\_TRAN + COST\_TREAT - REVE \qquad (3)$$

where *COST_TRAN* is the total transportation cost (NT$/day); *COST_TREAT* is the total treatment costs (NT$/day); *REVE* is the revenues (NT$/day).

The total transportation cost including the MSW, general industrial waste, recycled resources and food waste transported from collection station of districts to incinerators or MRF; button ash and fly ash from incinerators to landfills or button ash reuse facility; and the residues of recycled resources and button ash reusing transported to incinerators and landfills.

$$\begin{aligned} COST\_TRAN = & \sum_{i=1}^{m}\sum_{j=1}^{n} MSW_{ij} D_{ij} UTC \\ & + \sum_{I=1}^{M}\sum_{j=1}^{n} IMSW_{Ij} D_{Ij} UTC + \sum_{I=1}^{M}\sum_{h=1}^{q} LMSW_{Ih} D_{Ih} UTC \\ & + \sum_{i=1}^{m}\sum_{k=1}^{l} REC_{ik} D_{ik} UTC + \sum_{i=1}^{m}\sum_{k=1}^{l} COMP_{ik} D_{ik} UTC \\ & + \sum_{j=1}^{n}\sum_{h=1}^{q} FASH_{jh} D_{jh} UTC + \sum_{j=1}^{n}\sum_{h=1}^{q} BASH_{jh} D_{jh} UTC \\ & + \sum_{j=1}^{n}\sum_{e=1}^{g} BASH_{je} D_{je} UTC + \sum_{k=1}^{l}\sum_{j=1}^{n} RRFREM_{kj} D_{kj} UTC \\ & + \sum_{e=1}^{g}\sum_{h=1}^{q} BAREM_{eh} D_{eh} UTC \end{aligned} \qquad (4)$$

where *UTC* is the unit transportation cost (NT$/ton-km); D_{xy} is the distances from x ($x = i, I, j, k, e$) to y ($y = j, h, k, e$) (km); MSW_{ij} is the amount of MSW flow from districts (i) to incinerators (j) (ton/day); $LMSW_{Ij}$ and $IMSW_{Ih}$ is the amount of general industrial waste separately transported from municipality (I) to incinerators (j) and landfills (h) (ton/day); REC_{ik} and $COMP_{ik}$ is the amount of recycled resources and food waste transported from districts (i) to MRF (k) (ton/day);

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$FASH_{jh}$ is the amount of fly ashes transported form incinerators (j) to landfills (h) (ton/day); $BASH_{jh}$ and $BASH_{je}$ is the amount of button ashes transported from incinerators (j) to landfills (h) or reuse facility (e) (ton/day); $RRFREM_{kj}$ and $BAREM_{eh}$ is residual of MRF and button ash reusing facility transported to incinerators(j) and landfills(h) (ton/day).

$$\begin{aligned} COST\_TREAT &= \sum_{j=1}^{n}(MC_j \sum_{i=1}^{m} MSW_{ij}) \\ &+ \sum_{j=1}^{n}(IMC_j \sum_{I=1}^{M} IMSW_{Ij}) + \sum_{h=1}^{q}(LMC_h \sum_{I=1}^{m} LMSW_{Ih}) \\ &+ \sum_{k=1}^{l}(RC_k \sum_{i=1}^{m} REC_{ik}) + \sum_{k=1}^{l}(CC_k \sum_{i=1}^{m} COMP_{ik}) \\ &+ \sum_{e=1}^{q}(BAC_e \sum_{j=1}^{n} BASH_{je}) + \sum_{h=1}^{q}(FASHC_h \sum_{j=1}^{n} FASH_{jh}) \\ &+ \sum_{h=1}^{q}(BASHC_h \sum_{j=1}^{n} BASH_{jh}) + \sum_{j=1}^{n}(MC_j \sum_{k=1}^{l} RRFREM_{kj}) \\ &+ \sum_{h=1}^{q}(LMC_h \sum_{e=1}^{q} BAREM_{eh}) \end{aligned} \tag{5}$$

where MC_j and IMC_j is the treatment cost of MSW or residues after resource recycling and general industrial waste or residues after the button reusing in incinerators (j) (NT$/ton); LMC_h, $FASHC_h$ and $BASHC_h$ are the treatment costs of general industrial waste, fly ashes and button ashes in landfills (h), respectively (NT$/ton); BAC_e is the treatment cost of button reusing facility (e) (NT$/ton).

$$\begin{aligned} REVE &= \\ &\sum_{j=1}^{n} WETC_j^{\pm} EP_j SR_j (\sum_{i=1}^{m} MSW_{ij} + \sum_{k=1}^{l} RRFREM_{kj} + \sum_{I=1}^{M} IMSW_{Ij}) \\ &+ RP_k RR_k \sum_{i=1}^{m} REC_{ik} + CP_k CR_k \sum_{i=1}^{m} COMP_{ik} \end{aligned} \tag{6}$$

where $WETC_j$, EP_j and SR_j are the waste to electricity transfer coefficient (KWh/ton), the selling price of electricity (NT$/KWh) and the ratio of selling (%) to market in incinerators (j), respectively; RP_k and CP_k are the benefits of resource recycling and food waste reusing in MRF (k), respectively (NT$/ton); RR_k and CR_k are the recovery ratios in MRF (k), respectively (%).

For each district, the MSW, recycled resources and food waste it generates should be shipped to the available incinerators and MRF, respectively, as in (7), (8) and (9). For each municipality, the general industrial waste can be shipped to the available incinerators or landfills, as in (10). For each incinerator, the button ashes generated can be transported to the available landfills or button reusing facilities, and the fly ashes generated can only be transported to landfills, as in (11) and (12). The residues after resource recycling and button ashes reusing can be transported to incinerators and landfills, respectively, as in (13) and (14).

$$GENE_i(1-\alpha_i-\beta_i) = \sum_{j=1}^{m} MSW_{ij} \tag{7}$$

$$GENE_i \alpha_i = \sum_{k=1}^{l} REC_{ik} \tag{8}$$

$$GENE_i^{\pm} \beta_i = \sum_{k=1}^{l} COMP_{ik} \tag{9}$$

$$IGENE_I = \sum_{j=1}^{m} IMSW_{Ij} + \sum_{j=1}^{m} LMSW_{Ih} \tag{10}$$

$$\begin{aligned} &FASHGR_j(\sum_{i=1}^{m} MSW_{ij} + \sum_{k=1}^{l} COMPREM_{kj} + \sum_{I=1}^{M} IMSW_{Ij}) \\ &= \sum_{h=1}^{q} FASH_{jh} \end{aligned} \tag{11}$$

$$\begin{aligned} &BASHGR_j(\sum_{i=1}^{m} MSW_{ij} + \sum_{k=1}^{l} COMPREM_{kj} + \sum_{I=1}^{M} IMSW_{Ij}) \\ &= \sum_{e=1}^{q} BASH_{je} + \sum_{h=1}^{q} BASH_{jh} \end{aligned} \tag{12}$$

$$(1-RR_k)\sum_{i=1}^{m} REC_{ik} + (1-CR_k)\sum_{i=1}^{m} COMP_{ik} = \sum_{h=1}^{q} RRFREM_{kj} \tag{13}$$

$$(1-BASHR_e)\sum_{j=1}^{n} BASH_{je} = \sum_{h=1}^{q} BAREM_{eh} \tag{14}$$

where $GENE_i$ is the MSW generated in district (i); $IGENE_I$ is the general industrial waste generated in Taichung Special Municipality (I); the α_i and β_i are the ratios of recycled resources and food waste on MSW in district (i), respectively; $FASHGR_j$ and $BASHGR_j$ are the generation rates of fly ahs and button ash in incinerators (j), respectively.

For each incinerator, MRF and landfill, the mass conservation law should be satisfied, and their designed treatment capacities should not be exceeded:

$$\sum_{i=1}^{m} MSW_{ij} + \sum_{k=1}^{l} RRFREM_{kj} + \sum_{I=1}^{M} IMSW_{Ij} \le COEF_j CAP_j \tag{15}$$

$$\sum_{i=1}^{m} MSW_{ij} + \sum_{k=1}^{l} RRFREM_{kj} + \sum_{I=1}^{M} IMSW_{Ij} \ge PRO\_WASTE_j \tag{16}$$

$$\sum_{i=1}^{m} REC_{ik} + \sum_{i=1}^{m} COMP_{ik} \le COEF_k CAP_{kx} I_{kx} \tag{17}$$

$$\sum_{j=1}^{n} LMSW_{Ih} + \sum_{j=1}^{n} FASH_{jh} + \sum_{j=1}^{n} BASH_{jh} + \sum_{e=1}^{q} BAREM_{eh} \le CAP_h I_h \tag{18}$$

where $COEF_j$ and $COEF_k$ are the operation loadings (%) for incinerators (j) and MEF (k), respectively; the CAP_j, CAP_{kx} and CAP_h are the maximum design capacities for incinerator (j), MRF (k) and landfills (h), respectively (ton/day); *PRO_WASTEj* is the guaranteed quantity of MSW for incinerator (j); I_{kx} and I_h are binary integer variables.

The optimization model is established using the LINGO 8.0 software package.

IV. Scenarios Description

There are two scenarios evaluated in the optimization models developed in this study to minimize the total net costs of MSWM strategies and determine suitable number and sites of MRFs and landfills.

Scenario 1

In Taichung Special Municipality, the total amount of recycled resources and food wastes is approximately 1000 ton/day. In this scenario, 16 MRF candidate sites nearby existing landfills. The design capacities of the new MRFs can be either 100 or 200 ton/day. Each MRF must be operated above 50% of its design capacity and the total capacity of all MRFs can't exceed 1000 ton/day. The constraints can be shown as the following:

$$\sum_{i=1}^{m} REC_{ik} + \sum_{i=1}^{m} COMP_{ik} \ge 0.5\ CAP_{kx} I_{kx} \tag{19}$$

$$\sum_{k=1}^{l}\sum_{x=1}^{2} CAP_{kx} I_{kx} \le 1000 \tag{20}$$

$$\sum_{x=1}^{2} I_{kx} \le 1 \tag{21}$$

where the capacity of CAP_{kx} is either 100 or 200 ton/day.

Scenario 2

In this scenario, at most 4 landfills can be remained in Taichung Special Municipality. Conditionality constraint is shown as following:

$$\sum_{j=1}^{m} LMSW_{lh} + \sum_{j=1}^{n} FASH_{jh} + \sum_{j=1}^{n} BASH_{jh} + \sum_{e=1}^{g} BAREM_{eh} \ge CAP_h I_h \quad (22)$$

$$\sum_{x=1}^{2} I_h \le 4 \quad (23)$$

V. RESULTS AND DISCUSSION

The cost/revenue analysis data of the optimal solution of each scenario are summarized in Table 4. It can be found that the net daily costs of scenario 1 and 2 are NT$1,258,078 and NT$1,258,918, respectively. Fig. 4 shows that all of the MSW are transported to either Houli or Wurih incinerator, and Nantun incinerator is only assigned general industrial waste. The results of scenario 1 and scenario 2 indicates that 7 MRFs are suitable for Taichung Special Municipality, namly Taichung, Shengang, Shalu, Houli, Dadu, Dali and Taiping. The design capacity and throughput are shown in Table 4 and recycled resources from districts to MRFs are shown in Fig. 5. In scenario 1, there are 5 landfills are selected, although the operation loading of Taichung landfill is low. Fig. 6 shows that only 4 landfills are selected, including Taichung, Shengang, Houli and Wurih landfill**,** which results in a significant reduction of the treatment capacity of landfills. Therefore, throughputs of the Nantun incinerator increased about 28 ton/day to incinerate the general industrial wastes that may initially be disposed at landfills.

Table 4 The optimization solutions for scenario 1 and 2

Cost and benefits (NT$/day)				
Term	Scenario 1		Scenario 2	
Transportation cost	309,340		310,950	
Treatment cost	4,431,915		4,444,299	
Benefits	3,483,176		3,496,331	
Net	1,258,078		1,258,918	
MSW throughputs of incinerator (ton/day)				
Nantun	0		0	
Houli	765		765	
Wurih	819		819	
The general industrial waste throughputs of incinerator (ton/day)				
Nantun	603		631	
Houli	37		37	
Wurih	0		0	
The capacity and throughputs of MRF chosen (ton/day)				
MRF site	Capacity	Throughput	Capacity	Throughput
Taichung	200	200	200	200
Shengang	100	100	100	100
Shalu	100	100	100	100
Houli	100	100	100	100
Dadu	100	96	100	96
Dali	200	200	200	200
Taiping	200	200	200	200
The throughput of landfills (ton/day)				
Taichung	28		100	
Shengang	100		100	
Heping	0		0	
Waipu	0		0	
Dajia	0		0	
Sinshe	0		0	
Longjing	0		0	
Shalu	100		0	
Houli	100		100	
Daan	0		0	
Dadu	0		0	
Wurih	49		50	
Dali	0		0	
Dongshih	0		0	
Wufong	0		0	
Taiping	0		0	

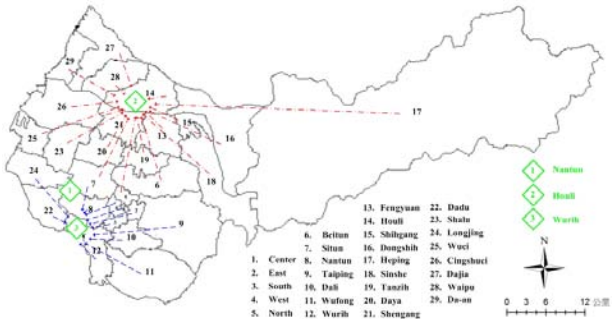

Fig.4 The MSW flows of Scenario1 and 2

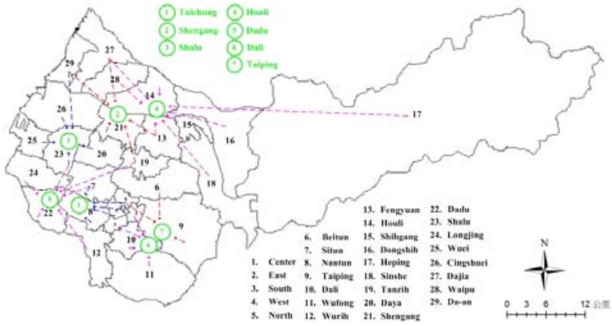

Fig.5 The recycled resources flows of Scenario1 and 2

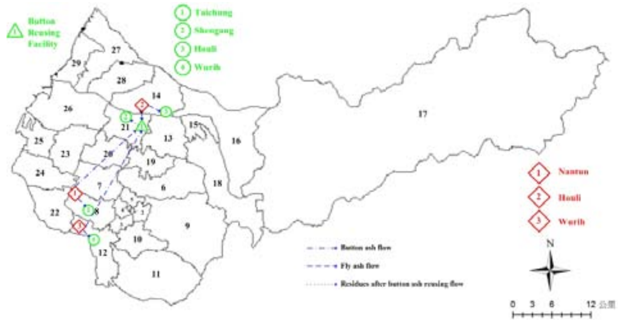

Fig.6 The flows of button ash, fly ash and residues

VI. CONCLUSION

A prototype MILP optimization model designed to help decision makers drawing up optimal MSWM strategies has been developed. It includes numerous unit processes related to transportation, treatment, waste-to-electricity, resource recycling, and disposal of MSW. The model is capable of analyzing the most economical strategies for the waste stream allocation of different MSWM scenarios, determining suitable sites and designed capacities of MRFs, and analyzing the necessary number of landfills. This tool should be very beneficial for MSW management policymaking for Taichung Special Municipality.

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