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Original Article

Development of a municipal solid waste dynamic model in Bangkok, Thailand

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Abstract

With the growing trend of municipal solid waste amount, Bangkok now faces a number of environmental problems. To properly manage wastes and plan for an effective waste management program in the long term, this study developed a municipal solid waste dynamic model with three involved parties: 1) the "Householder", 2) the "Government Officer", and 3) the "Scavenger". The relationships among the three key parties are examined through simulation results. The results indicate that, with the cooperation of all three parties, recyclable wastes can be completely sorted in 17 years. Policy testing is also conducted to effectively plan for recycling program implementation. The results reveal the importance of householder cooperation to successfully implement such a program. The developed dynamic model helps in better understanding the MSW situation in Bangkok, and plan for effective waste management.

Keywords: dynamic model, government officer, householder, municipal solid waste, scavenger

1. Introduction

Bangkok, the capital city of Thailand, has a population of almost 6 million people (9% of the total population), and 43 million visitors per year (Bangkok Metropolitan Administration [BMA], 2012; National Statistical Office [NSO], 2013). According to the Bangkok Metropolitan Administration (2012), the amount of recyclable and non-recyclable municipal solid waste (MSW) in Bangkok has been increasing steadily by 2% over the past decade, ranging from 8,200 to 9,700 tons per day. This accounts for 21% of the national total amount. It was found that 60% of these wastes can be recycled; however, only 12% are actually recycled, resulting in the remaining 8,000 tons being dumped into landfills (BMA, 2009; Kitjakosol, 2013).

The major failure of waste management in Bangkok is the inability in waste sorting between recyclable and non-recyclable wastes. More landfill space is then required, causing more environmental problems, such as water and air pollution (Greenpeace, 2013).

Based on Muttamara *et al.* (2004) and Manomaivibool (2005), three key parties involved in the waste management program include the "Householder", the "Government Officer", and the "Scavenger". However, the relationships among these key parties, and how they affect each other, are neglected. This paper, therefore, aims to develop a MSW dynamic model, utilizing a system dynamics (SD) methodology, to investigate the relationships among key parties involved in the waste recycling program, and strategically plan for effective waste management in Bangkok. It is expected that the developed model will assist in guiding the recycling program implementation over time.

2. Development of a MSW Dynamic Model

Many researchers, using stochastic, quadratic, fuzzy, interval, and mixed integer linear modeling techniques, have undertaken to deal with complex problems of waste management. Maqsood, Huang, and Zeng (2004), for example, developed an inexact two-stage mixed integer linear

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programming model to manage waste allocation and facility expansion planning. Li, Huang, Liu, Zhang, and Nie (2008) developed an inexact stochastic quadratic programming to optimize the cost of waste transportation to landfills. The results can be used as a guideline to decide on the best policy under various environmental, economic, and system reliability constraints. Xu, Huang, and Shao (2014) developed a solid waste management model with fuzzy random parameters to identify desired waste management strategies with less environmental constraints.

The above researchers aimed at managing waste at a single point of time, and did not consider the system over a time horizon. To effectively plan for waste management, there is a need to investigate the interactions among key factors influencing MSW management over time. This study, therefore, utilizes the SD modeling technique to develop the MSW dynamic model, as it is a methodology to examine cause-and-effect relationships (Sterman, 2000). The technique provides the ability to build a model of a decision environment, and then simulate how the model elements interact over time (Wolstenholme, 1994). It consist of four main elements, including stock, flow, convertor, and connector. Stock is a collection of stuff, an aggregate that flows into or out of stock. Convertor, on the other hand, is an equation o r a constant. A convertor is connected to a flow or a stock through a connector.

SD methodology has been applied in a wide variety of disciplines, such as economics, business, construction safety, water supply, and waste management. Chaerul, Tanaka, and Ashok (2007), for example, developed a SD approach to determine the interactions among factors in a hospital waste management system in Jakarta, Indonesia. Kollikkathara, Feng, and Danlin (2010) developed a SD model of landfill capacity, environmental impacts, and financial expenditure to better plan for the urban waste management system in Newark, USA. Mohamed and Chinda (2011) developed a construction safety culture model to plan for an effective safety implementation in the construction industry in Thailand. Ahmad (2012) used SD modeling to predict the MSW generation, collection, disposal, and electricity generation from MSW, and to assess the budget needs for MSW management in Delhi, India. Hajiheydari and Zarei (2013) developed a SD model to improve quality and decrease production cost in an electronics organization. Park, Jeon, and Jung, (2013) utilized a SD modeling technique to identify key factors, as well as their relationships, in water supply management, and examine the best policy for achieving an efficient water supply system.

In this study, the MSW management in Bangkok, Thailand, is investigated. According to Muttamara, Leong, Somboonjaroensri, and Wongpradit (2004) and Manomaivibool (2005), the flow (Figure 1) starts from wastes collected from householders by the government officers at night to avoid traffic in rush hours. The government officers then collect and partially sort the recyclable from th e non-

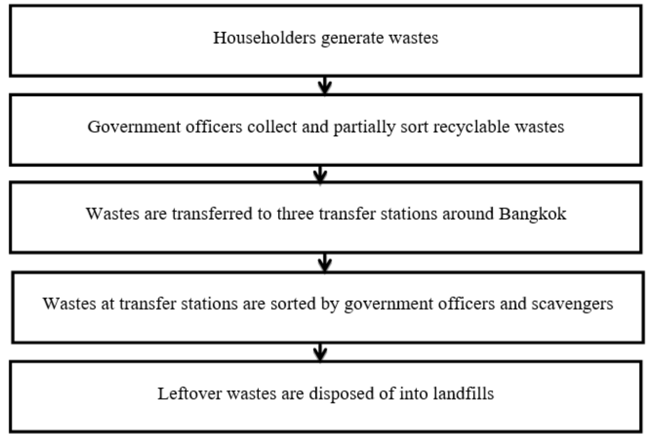


Figure 1. Flow of MSW in Bangkok.

recyclable wastes. The collected wastes are sent to the three transfer stations located around the perimeter of Bangkok; the Tharaeng, the Nongkam, and the Onnuch transfer stations (Manomaivibool, 2005). At the transfer stations, the recyclable wastes are further sorted by the government officers and scavengers (Muttamara *et al.*, 2004; Pungphum, 2013). The leftover wastes will, at the end, be sent to landfills.

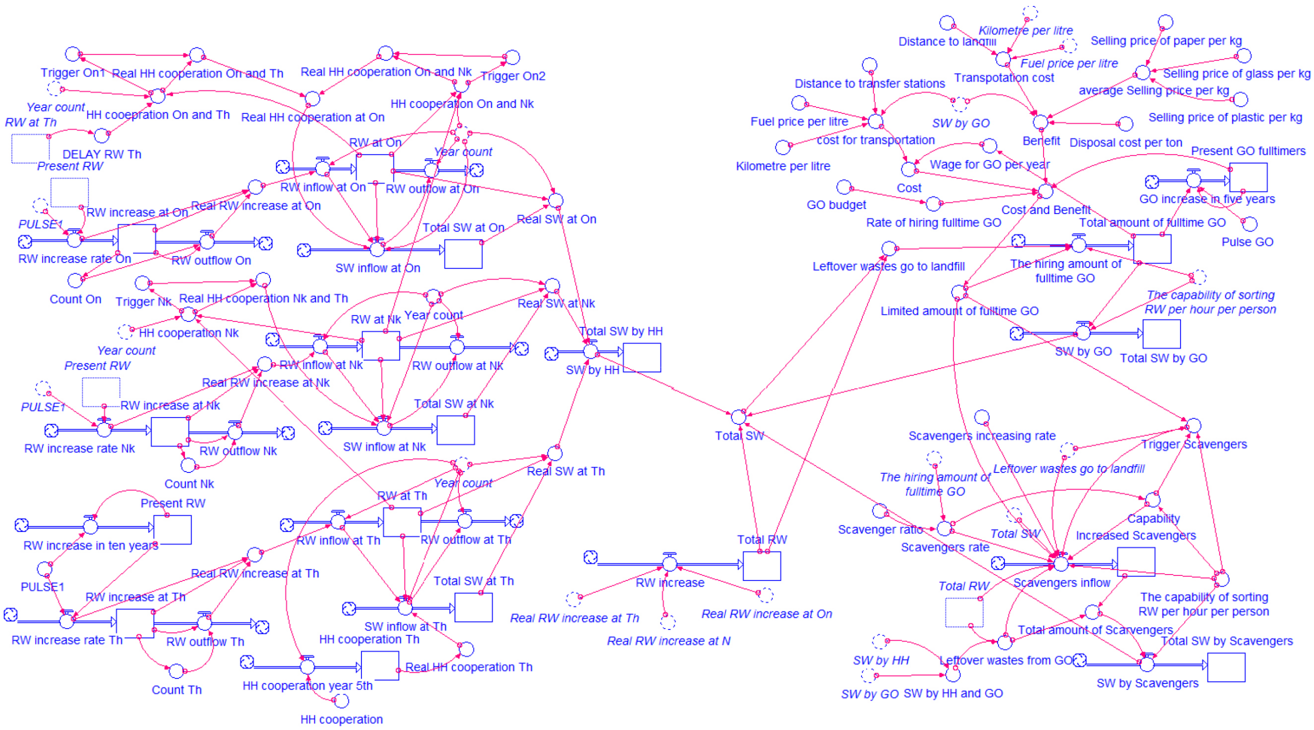
The MSW dynamic model consists of four models, namely 1) the “Householder” model, 2) the “Government Officer” model, 3) the “Scavenger” model, and 4) the “Total Sorted Waste” model, as shown in Figure 2.

2.1 Householder dynamic model

Households are a major source of MSW generation (Eurostat, 2012). Figure 3 shows the Householder dynamic model. It represents the amount of wastes sorted by the householders through the recycling program implementation. The model is divided into four sub-models: 1) the Tharaeng sub-model, 2) the Nongkam sub-model, 3) the Onnuch sub-model, and 4) the Householder Total Sorted Waste sub-model.

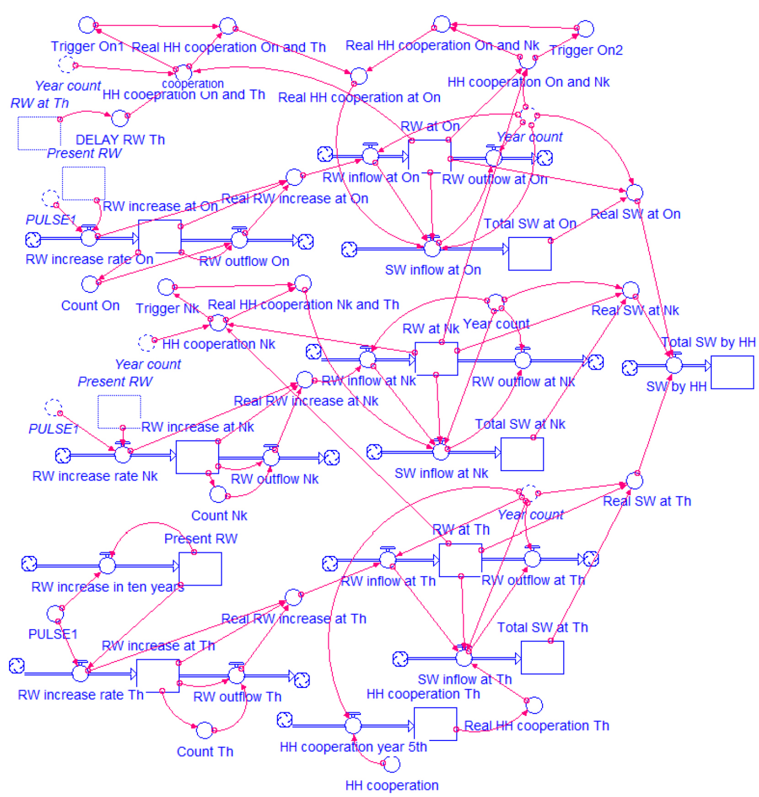
2.1.1 Tharaeng sub-model

Generally, the Tharaeng transfer station deals with 2,400 tons of wastes per day. This station has the smallest capacity among the three transfer stations (around 25.8% of the total wastes). Most of the wastes, once received at the three transfer stations, will be transferred and disposed of to landfills. The recycling program implementation is, therefore, necessary to effectively sort the recyclable from the non-recyclable wastes before dumping into landfills (European Environmental Agency [EEA], 2013). In the Tharaeng sub-model, the “Total_SW_at_Th” represents the total amount of sorted wastes accumulated at this station each year (Equation 1).



Note: Th = Tharaeng, Nk = Nongkam, On = Onnuch, HH = Householder, GO = Governent officer, RW = Recyclable waste, and SW = Sorted waste.

Figure 2. MSW dynamic model.



Note: Th = Tharaeng, Nk = Nongkam, On = Onnuch, RW = Recyclable waste, and SW = Sorted waste.

Figure 3. Householder dynamic model.

Total_SW_at_Th (t) =
Total_SW_at_Th (t - dt) + (SW_inflow_at_Th) * dt (1)

The "SW_inflow_at_Th" inflow represents the amount of wastes collected from the householders in Tharaeng and nearby areas. The amount of wastes collected is influenced by the income status of the householders and the householders' cooperation in the recycling program (Equation 2). This is partly confirmed by Sankoh, Yan, and Conteh (2012) that different income status reflects different amounts of waste generation. The cooperation of householders in the recycling program is set in this study as 4, 5, 7.5 and 12.5% in the first four years, respectively. These percentages derive from the previous recycling program implemented in various cities in Thailand. (Institute for Local Government Initiatives, 2003, 2004; Phitsanulok Town Municipality, 2008).

SW_inflow_at_Th =
If (RW_at_Th > 1) then (If (Year_count = 1) then (0.04 * RW_at_Th) else if (Year_count = 2) then ((0.05 * RW_at_Th)) else if (Year_count = 3) then (0.075 * RW_at_Th) else if (Year_count = 4) then (0.125 * RW_at_Th) else (RW_at_Th * Real_HH_cooperation_Th)) else (RW_inflow_at_Th) (2)

Based on the Pollution and Control Department (PCD, 2013), the amount of wastes transferred to Tharaeng station increases by 16 percent every 10 years. This, in turn, increases the total recyclable wastes at this station each year (Equation 3).

RW_at_Th (t) =
RW_at_Th (t - dt) + (RW_inflow_at_Th – RW_outflow_at_Th) * dt (3)

2.1.2 Nongkam sub-model

In the Nongkam sub-model, the "Total_SW_at_Nk" represents the total amount of sorted wastes accumulated at this station each year. It is a function of the "SW_inflow_at_Nk" inflow (Equations 4 and 5).

Total_SW_at_Nk (t) =
Total_SW_at_Nk (t - dt) + (SW_inflow_at_Nk) * dt (4)

SW_inflow_at_Nk =
If (Real_HH_cooperation_Nk_and_Th < 1) then (If then (0) else if (Year_count >= 2) then RW_at_Nk * Real_HH_cooperation_Nk_and_Th else 0) else RW_inflow_at_Nk + RW_at_Nk (5)

In this study, the recycling program implementation at this station is initiated in year 2 following the implementation at Tharaeng station (Equation 6). This is due to the use of the Tharaeng station (with the smallest as a case study for the Nongkam station).

HH_cooperation_Nk =
If (RW_at_Nk > 0) then (If (year_count >= 2) then 1 - (RW_at_Th/(RW_at_Nk * 0.73)) else 0) else 1 (6)

2.1.3 Onnuch sub-model

In the Onnuch sub-model, the "Total_SW_at_On" represents the total amount of sorted waste accumulated at the station each year. It is a function of "SW_inflow_at_On" inflow (Equations 7 and 8).

Total_SW_at_On (t) =
Total_SW_at_On (t - dt) + (SW_inflow_at_On) * dt (7)

SW_inflow_at_On =
If (Real_HH_cooperation_at_On < 1) then (If (Year_count <= 2) then (0) else if (Year_count >= 3) then (RW_at_On * Real_HH_cooperation_at_On) else 0) else RW_inflow_at_On + RW_at_On (8)

In this study, the recycling program implementation at Onnuch station is initiated in year 3 following the implementation at Tharaeng and Nongkam stations (Equation 9).

Real_HH_cooperation_at_On =
(Real_HH_cooperation_On_and_Nk + Real_HH_cooperation_On_and_Th) / 2 (9)

2.1.4 Householder total sorted waste sub-model

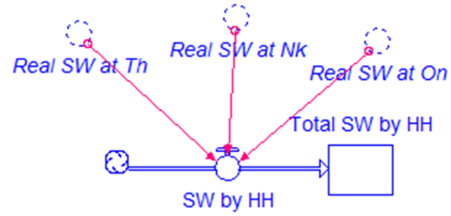
Figure 4 shows the Householder Total Sorted Waste sub-model. The "Total_SW_by_HH" represents the total amount of sorted wastes, accumulated by householders, each year (Equation 10). The "SW_by_HH" inflow, on the other hand, represents the amount of sorted wastes from the three transfer stations (Equation 11).

Total_SW_by_HH (t) =
Total_SW_by_HH (t - dt) + (SW_by_HH) * dt (10)

SW_by_HH =
Real_SW_at_On + Real_SW_at_Nk + Real_SW_at_Th (11)

2.2 The government officer dynamic model

After the wastes are collected by the government officers, they will be transferred to the three transfer stations. These wastes are then sorted by the government officers at the transfer stations (Muttamara *et al.*, 2004; Pungphum, 2013). The Government Officer dynamic model is illustrated in Figure 5. The "Total_SW_by_GO" represents the total



Note: HH = Householder, Th = Tharaeng, Nk = Nongkam, On = Onnuch, and SW = Sorted waste.

Figure 4. Householder Total Sorted Wastes sub-model.

amount of wastes sorted by fulltime officers each year. It is a function of "SW_by_GO" inflow (Equations 12 and 13).

Total_SW_by_GO (t) =
Total_SW_by_GO (t - dt) + (SW_by_GO) * dt (12)

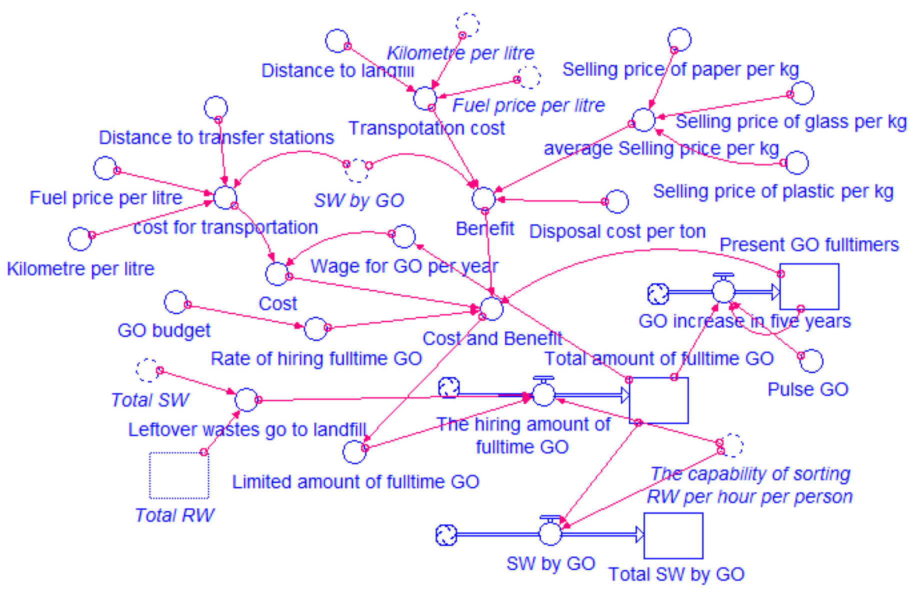
SW_by_GO =
(The_capability_of_sorting_RW_per_hour_per_person * 8 * Total_amount_of_fulltime_GO * 246) (13)

The "Total_amount_of_fulltime_GO" represents the amount of fulltime officers. This increases each year through the hiring process. "The_hiring_amount_of_fulltime _GO" inflow, on the other hand, represents the new fulltime officers that are hired each year (Equations 14 and 15). The hiring decision is based on the assumption that the benefits of the recycling program implementation are higher than the costs of the implementation (Equation 16). Benefits, in this study, include the saving in the transportation cost to landfill and the revenue from sorted wastes sales. Costs, on the other hand, refer to the wages of fulltime government officers and the transportation cost to the recycling shops.

Total_amount_of_fulltime_GO (t) =
Total_amount_of_fulltime_GO (t - dt) + (The_hiring_amount_of_fulltime_GO) * dt (14)

The_hiring_amount_of_fulltime_GO =
if (Leftover_wastes_go_to_landfill > 0) then MIN(INT((Leftover_wastes_go_to_landfill) / ((The_capability_of_sorting_RW_per_hour_per_person) * 246 * 8)), INT (Limited _amount _of_fulltime_GO)) else (0) (15)

Cost_and_Benefit =
if (Cost > Benefit) then (0) else if (Cost < Benefit) then (Present_GO_fulltimers * Rate_of_hiring_fulltime_GO) else (0) (16)



Note: GO = Government officer, SW = Sorted waste, and RW = Recyclable waste.

Figure 5. Government Officer dynamic model.

Based on the Bangkok Metropolitan Administration Budget Department (2013), the amount of fulltime officers ranges from 2 to 12%, each year; however, it should not exceed 400 persons per year, based on the allowable budget. The leftover wastes from government officers are then managed by the scavengers.

2.3 Scavenger dynamic model

Figure 6 shows the Scavenger dynamic model. This model describes the amount of sorted wastes from the scavengers. The "Total_SW_by_Scavengers" represents the total amount of sorted wastes accumulated each year. It is a function of the "SW_by_Scavengers" inflow (Equations 17 and 18).

Total_SW_by_Scavengers (t) =
Total_SW_by_Scavengers (t - dt) +
(SW_by_Scavengers) * dt (17)

SW_by_Scavengers =
Total_amount_of_Scavengers * (The_capability_of_sorting_RW_per_hour_per_person) * 8 * 365 (18)

The "Total_amount_of_Scavengers" represents the amount of additional scavengers each year (Equation 19). According to Pungphum (2013), the current waste sorting capacity is 900 tons/day or around 3,666 persons at the three transfer stations. The more wastes at the transfer stations, the more scavengers, as more recyclable wastes can be sorted and sold at the recycling shops. The maximum amount of scavengers at the three transfer stations must, however, not exceed 9,000 people due to the limited space at the transfer stations (Equation 20).

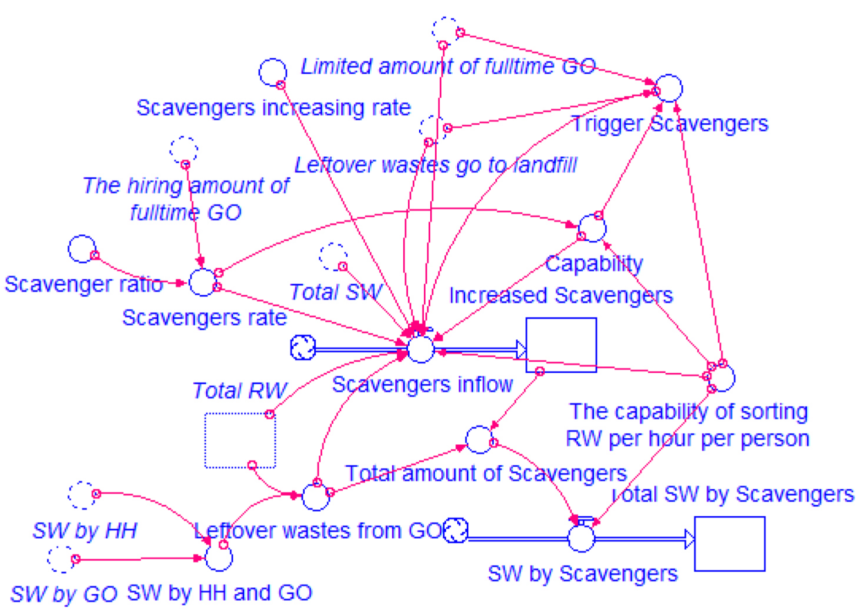
Total_amount_of_Scavengers =
If Leftover_wastes_from_GO = 0 then (If (Increased_Scavengers > 9000) then 9000 else Increased_Scavengers) else random (6000, 9000, 1) (19)

Scavengers_inflow =
If Leftover_wastes_from_GO = 0 then (if (Trigger_Scavengers = 0) then (if (Total_SW < Total_RW) then (If (Total_RW - Total_SW > Capability) then (Scavengers_rate * Scavengers_increasing_rate) else (Leftover_wastes_go_to_landfill - (INT (Limited_amount_of_fulltime_GO) * The_capability_of_sorting_RW_per_hour_per_person * 8 * 246)) / (The_capability_of_sorting_RW_per_hour_per_person * 8 * 365)) else (0)) else 0) else 0 (20)

2.4 Total sorted waste dynamic model

The Total Sorted Waste dynamic model represents the sum of the wastes sorted at the three transfer stations, as shown in Equation 21.

Total_SW =
If (Total_RW > (SW_by_GO + SW_by_HH + SW_by_Scavengers)) then (SW_by_GO + SW_by_HH + SW_by_Scavengers) else Total_RW (21)



Note: HH = Householder, GO = Government officer, SW = Sorted waste, and RW = Recyclable waste.

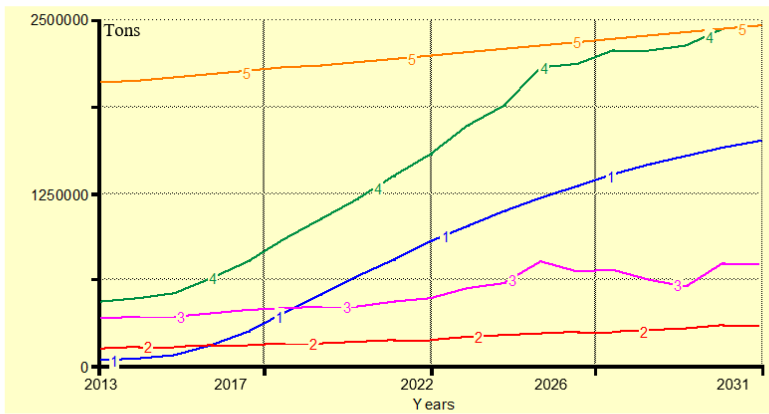
Figure 6. Scavenger dynamic model.

3. Simulation Results of Base Case Scenario

In the "base case" scenario, all initial values of the MSW dynamic model are set to reflect the real situations in Bangkok. For example, the initial amount of the MSW generation is 9,237 tons; the current capacity of government officers in waste sorting is 107,779 tons; and the number of scavengers at the transfer stations are 3,666 persons. The simulation results are illustrated in Figure 7 and Table 1. It is clear that the amount of sorted wastes increase as time increases.

As shown in the graphical results, the major proportion of the sorted wastes in the early years comes from the scavengers. This is due to the low participation from the householders in the early phase of the recycling program. Once the recycling program continues, the amount of sorted wastes achieved from the householders increases (from year 2017 onwards, Figure 7) and surpasses those achieved from the government officers and scavengers.

The amount of sorted wastes from the government officers increases in a steady rate (Figure 7). This is due to the limited budget of the Department of Environment Bangkok in



Note: 1 - 5 represent the graphical results of sorted wastes by the Householder, the Government Officer, the Scavenger, the Total Sorted Waste, and the Total Recyclable Waste, respectively.

Figure 7. Graphical results of sorted wastes and recyclable wastes in base case scenario.

Table 1. Amount of sorted wastes and number of government officers and scavengers.

Year	Sorted waste (tons)				Recyclable waste (tons)	No. of government officers (persons)	No. of scavengers (persons)
	By Householders	By Government Officers	By Scavengers	Total amount			
2013	13,621	107,780	328,435	449,836	2,033,044	1,785	3,666
2014	24,332	109,893	331,571	465,796	2,054,838	1,820	3,701
2015	57,534	113,456	337,484	508,473	2,076,632	1,879	3,767
2016	128,008	123,720	364,181	615,909	2,098,427	2,049	4,065
2017	228,192	130,785	379,412	738,389	2,120,221	2,166	4,235
2018	354,973	138,634	397,240	890,847	2,142,015	2,296	4,434
2019	494,411	144,069	407,005	1,045,485	2,163,809	2,386	4,543
2020	625,394	147,269	411,933	1,184,596	2,185,604	2,439	4,598
2021	752,821	158,741	440,422	1,351,985	2,207,398	2,629	4,916
2022	878,590	170,214	469,001	1,517,805	2,229,192	2,819	5,235
2023	995,898	185,007	537,539	1,718,445	2,250,986	3,064	6,000
2024	1,101,809	194,909	572,890	1,869,609	2,276,268	3,228	6,394
2025	1,196,758	207,106	740,620	2,144,484	2,301,549	3,430	8,266
2026	1,282,539	224,617	660,808	2,167,964	2,326,830	3,720	7,375
2027	1,363,519	228,602	680,728	2,272,849	2,352,111	3,786	7,598
2028	1,438,001	232,889	596,386	2,267,276	2,377,393	3,857	6,656
2029	1,505,091	249,554	550,181	2,304,826	2,402,674	4,133	6,141
2030	**1,564,170**	**269,419**	**719,994**	**2,427,955**	**2,427,955**	**4,462**	**8,036**

hiring more fulltime officers. The amount of sorted wastes from the scavengers, on the other hand, increases over time due to the increased number of scavengers each year. However, after the year 2022, less than 50% of the total recyclable wastes are sent to transfer stations as a result of the effective recycling program implementation. This, in turn, attracts less scavengers in sorting wastes.

With the cooperation from householders and the government officers, all the recyclable wastes could be sorted in 17 years (Figure 7). Only non-recyclable wastes are consequently transferred to landfills. This requires a total of 4,462 government officers and 8,036 scavengers.

4. Policy Testing Analysis

To further validate the model, and examine the real practices of recycling program implementation overtime, a policy testing analysis is performed. In this study, three key parameters within the three key models (the "Householder", the "Government Officer", and the "Scavenger" dynamic models) are selected for the analysis: (1) the "HH_cooperation", (2) the "GO_budget", and (3) the "Scavengers_increasing_rate" (Table 2). These parameters are important in the successful implementation of the recycling program. The value of these parameters is changed in each run, reflecting the pessimistic to the optimistic scenarios. It is expected that when these parameter values are high, the amount of sorted wastes are high.

4.1 HH_cooperation parameter

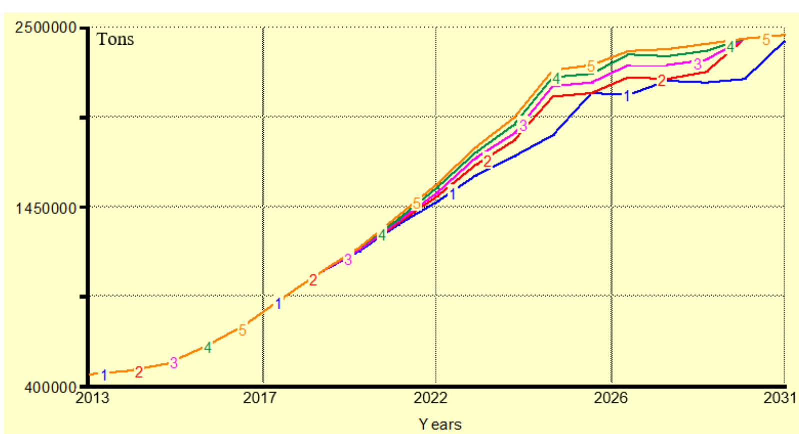
The "HH_cooperation" refers to the increasing percentages of householders' cooperation in recycling program implementation. In the base case scenario, the co-operation of households increases at the rate of 3% each year as the recycling program continues. In the policy testing analysis, this parameter varies from 0 to 6%, reflecting no cooperation from householders to the double of the current status.

Figure 8 shows the simulation results when the values of the "HH_cooperation" are changed. It is clear that low cooperation of householders reflects low amount of sorted wastes. This is consistent with Noonin (2004), who stated that householders are the most important actor in waste reduction and recycling. The waste recycling programs must be established from the point of generation, collection, and transport in order to enhance recovery (Luanratana, 2004).

Table 2. Values of three parameters for the policy testing analysis.

Parameter name	Description	Value (percentage)
HH_cooperation	The percentage of householder cooperation in recycling program implementation.	0, 0.015, 0.03, 0.045, 0.06
GO_budget	The increasing rate of environmental-related budgets for hiring more government officers.	0.02, 0.05, 0.08, 0.11, 0.14
Scavenger_increasing_rate	The increasing rate of additional scavengers in transfer stations	0, 0.3, 0.6, 0.9, 1.2

Note: HH = Householder, GO = Government officer.



Note: 1 - 5 represent the graphical results when the values of "HH_cooperation" are changed to 0, 0.015, 0.03, 0.045, and 0.06, respectively.

Figure 8. Total amount of sorted wastes when values of "HH_cooperation" are changed.

4.2 GO_budget parameter

The "GO_budget" refers to the increasing of allowable budget in hiring more fulltime officers. This parameter varies from 2–14% increase in budget allowance. This is based on the budgets of the Department of Environment Bangkok in the last six years, with the highest increasing rate of 14%. The graphical results show that when the budget is increased, the amount of sorted wastes is increased (Figure 9).

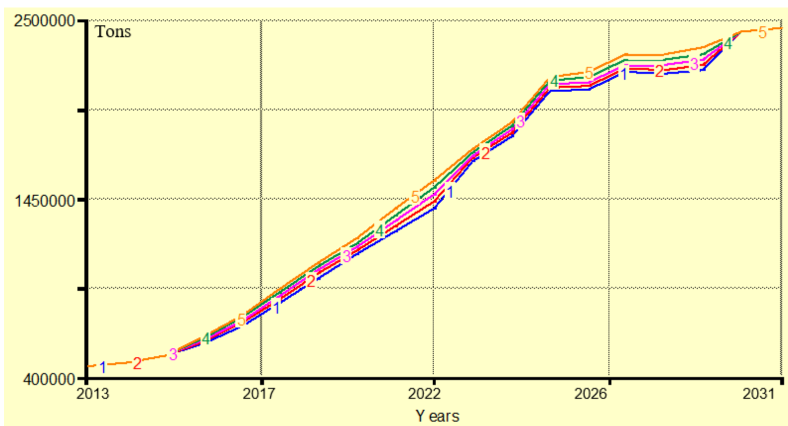
Nevertheless, the available budget is always limited. The maximum increase in hiring budget might not be appropriated in real practices. A number of training courses, therefore, might be possible to enhance the officers' skill in waste sorting.

4.3 Scavenger_increasing_rate parameter

The "Scavenger_increasing_rate", refers to the increasing rate of the additional scavengers at transfer stations. It ranges from 0 to 1.2 times of the current amount. Graphical results in Figure 10 prove there is a higher amount of sorted wastes when more scavengers are added in the system.

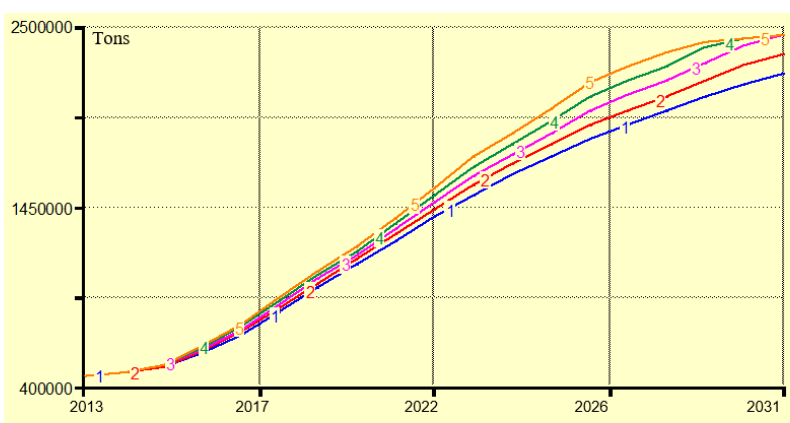
5. Conclusions

With the growing trend of MSW amount, Bangkok now faces with a number of environmental problems, such as water and air pollution. To overcome these problems, the MSW dynamic model is developed in this study to examine the relationships among three key parties (the "Householder", the "Government Officer", and the "Scavenger") of waste management in Bangkok, and plan for effective waste management in the long term. Data used in the model simulation, such as total waste amount, number of government officers, and householder cooperation in the recycling program implementation, are collected to reflect real practices in the present.



Note: 1 - 5 represent the graphical results when the values of "GO_budget" are changed to 0.02, 0.05, 0.08, 0.11, and 0.14, respectively.

Figure 9. Total amount of sorted wastes when values of the "GO_budget" are changed.



Note: 1 - 5 represent the graphical results when the values of "Scavenger_increasing_rate" are changed to 0, 0.5, 1, 1.5, and 2, respectively.

Figure 10. Total amount of sorted wastes when values of "Scavenger_increasing _rates" are changed.

In the “base case” simulation, the results show that, in the early phase of recycling program implementation, the major proportion of sorted wastes comes from scavengers. This is due to the low participation of the householders. The amount of sorted wastes by government officers has steadily increased, based on the available budget to hire new fulltime officers.

Once the recycling program continues, the householders take a major role in sorting and recycling wastes. More waste is sorted at the source (households), and less waste is collected and transferred to transfer stations. This attracts fewer scavengers at transfer stations. The results show that all recyclable wastes will be completely sorted in 17 years (year 2030) with the cooperation from the householders and the government officers.

Policy testing is also performed to examine the real practices of recycling program implementation over time. In this study, three key parameters, including the “HH_cooperation” (the householders’ cooperation), the “GO_budget” (the government budget), and the “Scavenger_increasing_rate” (the number of scavengers) are tested with different policies, and the results prove their importance in successful recycling program implementation. The householders’ cooperation is to be found the most important factor in recycling program implementation, as higher cooperation from householders results in a higher amount of sorted wastes.

More government officers lead to more sorted wastes. However, the increase in government budget for new officers might not be appropriated. A number of training courses, therefore, might be given to enhance the officers’ skill in waste sorting. The developed dynamic model helps in better understanding the MSW situation in Bangkok, and plan for an effective waste management. Data used in this study are, however, based on Bangkok.

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