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Application of system dynamics model for municipal solid waste generation and landfill capacity evaluation in Singapore

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Abstract

In recent years, waste generation in Singapore with rapid economic and population growth as well as change of consumption patterns has acquired more and more attention from the public and the government. On this perspective, sustainable development has become an effective course for Singapore's municipal solid waste (MSW) management system. Therefore, a system dynamics (SD) model for MSW management was developed to explore whether the current waste disposal capacity can meet the increasing amount of waste generation. Five different scenarios were applied in order to identify the best strategy for protection of the environment without inhibiting the growth of the economy. The System Dynamics model was used to evaluate the different strategies and polices made by public or stakeholders taking into consideration multiple feedbacks like population, economy growth and waste disposal subsystems (landfill, recycling and incineration). According to the results, scenario II is recommended since it covers the requirement for sustainable growth of economy and environmental protection without exceeding landfill capacity.

Keywords: *municipal solid waste, Singapore.*

1. INTRODUCTION

Singapore is a small tropical country with dense populations (land area 714.3 km^2, population 5.3 million, population density 7257 per km^2, average temperature 24.7-31.3^{o}C, mean relative humidity 73%) (Department of Statistics, 2011). In Singapore, the total annual MSW generation has increased from 4.7 million tonnes in 1996 to 6.9 million tonnes in 2011. Similarly, the domestic waste also shows increasing tendency – from 1.31 million tonnes in 1998 to 1.64 million tonnes in 2011. According to NEA (2011), the daily output of solid waste in Singapore has escalated from an average refuse output of 1260 tonnes/day in 1970 to 7700 tonnes/day in 2001 and to 7000 tonnes/day in 2005 (Zhang, et al., 2010). In terms of waste production, rapid economic and population growth continues to stress the solid waste disposal.

Municipal solid waste (MSW) management is an integrated and complex system which often involves sophisticated interactions and multiple feedbacks associated with environmental effects, economic development patterns, population, etc (Kollikkathara et al., 2010). The SD is an innovative approach which utilizes the feedback loops, stocks and flows in order to understand the behavior of complex systems (Chen and Wang, 1996). By considering the interactions among a number of related social, economical, environmental and regulatory systems using different scenarios, an integrated concept of the whole system can be achieved. Since the system dynamics concept appeared in 1960s, it has been applied in different practices such as policy experiments (Mohapatra et al., 1994), environmental impact assessment (Vizayakumar and Mohapatra, 1993), solid waste management (Mashayekhi, 1993; Karavezyris et al., 2002), MSW generation and landfill capacity evaluation (Kollikkathara et al., 2010), assessment and mitigation of greenhouse gas emissions (Shalini et al., 2006) investigations of methane emissions from rice cultivation (Anand et al., 2005), water and wastewater management (Stave, 2003), environmental planning (Guo et al., 2001; Guneralp and Barlas, 2003), environmental sustainability (Saysel et al., 2002), etc. However, the modeling of MSW generation and landfill capacity evaluation under different socio-economic condition is still missing. This study is based on a predictive decision support tool for waste generation which utilizes socio-economic, population and disposal capacity parameters from National Environmental Agency (NEA) of Singapore, Singapore country statistics and the Singapore Green Plan 2012.

2. SYSTEM DYNAMICS MODEL FOR SINGAORE MSW MANAGEMENT

In order to better represent the waste management system, three subsystems - population, economy and waste disposal has been included in SD model. Fig.1 gives the flow diagram for Singapore MSW production. A flow diagram is created from the casual loop diagram and dynamo equations. For the population subsystem, the population birth is the inflow while the population death is the outflow, and both are affected by the birth rate and death rate respectively. The main dynamo equations are indicated as follows:

(1) Total population = INTEG(Birth–Death)

(2) Birth rate = (Birth rate lookup(Time))*Birth rate adjustment

For the economy subsystem, the industrial GDP serves as the direct influence to the industrial waste generation, while the amount of waste generated per dollar is another factor. In addition, the industrial GDP growth rate which is important parameter for the economic development level, indirectly determines the industrial waste generation. The dynamo equations are listed:

(1) Industrial waste generation = Industrial GDP*Waste generation per dollar

(2) Industrial GDP- INTEG(Industrial GDP growth)

(3) Industrial GDP growth= Industrial GDP*Industrial growth rate

For the waste disposal subsystem, domestic and industrial waste generation consist the total waste disposal. Incineration, landfill and recycle are three main approaches for total MSW disposal. The accumulation of landfill (represent as status) is used to calculate the landfill capacity. The main equations are listed as follows:

(1) Total waste generated= Total wastes disposed + Total waste recycled

(2) Landfill capacity=INTEG (-Rate of filling)

(3) Rate of filling= Unit volume of compacted waste and soil*Waste to landfill

(4) Non-treated wastes=Amount of waste generated-Amount of waste to incineration-Amount of waste to landfill-Amount of waste to recycle

3. SCENARIO GENERATION

According to subsystems, five scenarios were generated, the basic scenario (BS) and modified scenarios I, II, III and IV. Policy strategies based on current socio-economic condition, landfill capacity and waste management are implemented in all five scenarios. The SD model is run for a time period of 40 years starting from the baseline year of 2005.

The basic scenario is generated to simulate the population growth rate based on the historical data and simulated GDP growth rate without any other parameter modification. The total MSW generation, population growth, GDP and waste to landfill, etc. are calculated at yearly basis. For the year of 2005, Singapore's population was 4.3 million with a growth rate of 0.11. To analyze its functional relationship and other alternatives, a Lookup function is utilized by using a linear relationship to determine the values of the dependent variables. For the baseline scenario, the birth rate Lookup is 0.067s. Similarly, the growth rate of the industrial gross domestic product (GDP) is subjective related Lookup function which determined 0.049.

The rates of population growth and the GDP which directly and indirectly determine the amount of domestic and non-domestic are having a significant effect on the waste production. Population growth and GDP are chosen to generate four modified scenarios: (1) Scenario I with high economic growth rate and slow population growth rate; (2) Scenario II with high economic growth and high population growth rate; (3) Scenario III with low economic growth rate and high population growth rate; (4) Scenario IV with low economic growth and slow population growth rate.

The growth of population has direct influence on the domestic waste generation, therefore will add significant amount to the total waste generated. The average population of domestic waste generation is also another important factor, and due to the modern lifestyle, consumption pattern and waste collection methods, an increasing tendency of waste generation per capital per day is reasonable. Hence, the overall domestic waste generation is predicted to increase which will eventually add press to the current landfill capacity. The strategies of promoting recycle, applying collection fee according to the quantities of household waste and educating people to generate less waste could inhibit the growth of domestic waste.

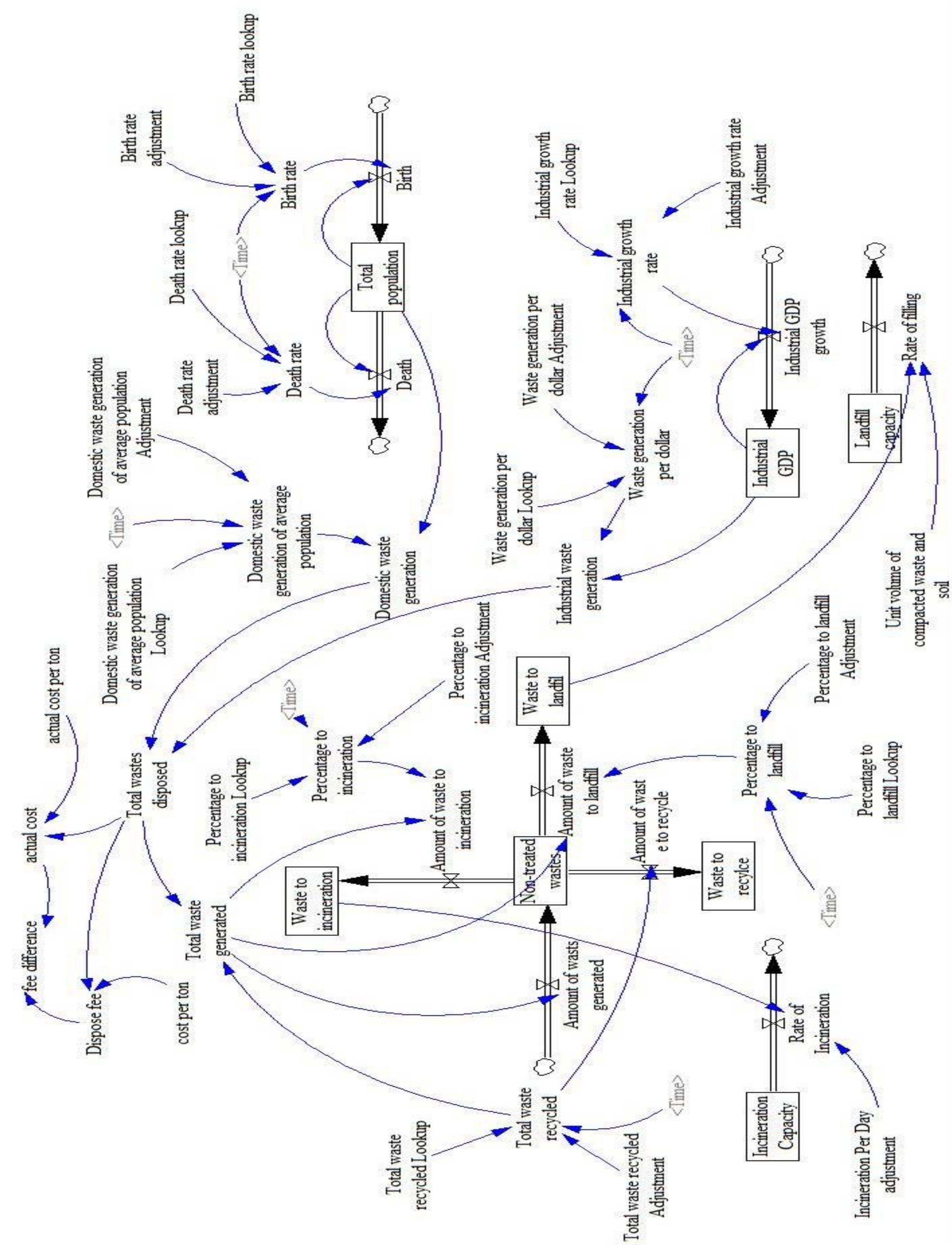

Fig. 1. Causal-loop diagram of system dynamics (SD) model for Singapore MSW production

The rate of MSW generation especially the non-domestic portion and landfill capacity are obviously linked to the economic activity in Singapore, the level and growth of GDP and the level of urbanization. Except the control of population growth, the integrated control of economic growth pattern can be one of the options to ease the waste stress. As mentioned earlier, the comparison of scenario I, II and III VI is made to analyze the impact of different economic growth rates on waste related issues including the contribution to the total MSW generation and the influence on the landfill, which is the last option in the MSW management decision in Singapore.

4. MODEL VALIDATION

The model should be validated in advance in order to identify the relationships between social-economic development and waste production in Singapore. Many parameters are considering in the SD model including the initial (reference year) MSW generation, disposal and composition of the MSW, population, house-hold size and GDP (year book of statistics Singapore 2011), and social-economical factors and control target (SGP 2012), landfill capacity, incineration capacity, recycle composition and collection rate from National Environmental Agency (NEA). Past data related to the specific waste composition was difficult to obtain due to the insufficient record, however, NEA have efficiently maintained a good database on waste recycling and collection since 1999. Thus, the model development and validation were confined within this period of time.

For historical validation, the total MSW generation is selected. Past data from 1999 until 2005 was incorporated in the model and simulations were implemented. As seen in Fig. 2, the model shows good agreement with the actual value. There is an increasing trend for the actual and simulated data.

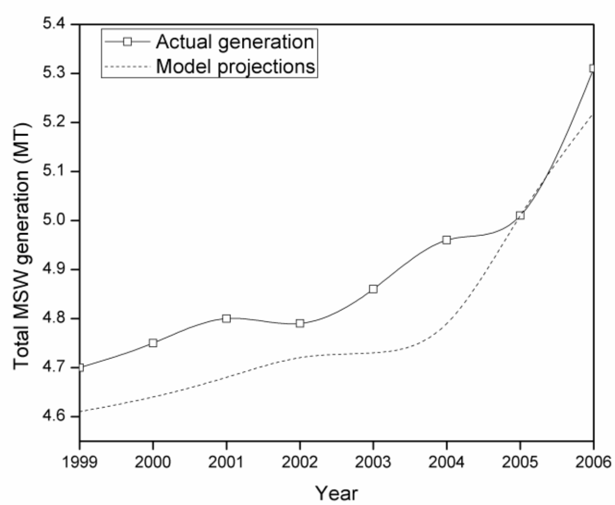

Fig. 2. Comparison of total MSW generation between model projections and actual generation.

The structural validation tests are applied to the overall model building process detecting the structural flaws in the model. Therefore, these tests were made simultaneously throughout the model building process. First, the model simulates the total population keeping the present rates of population growth rate, and then switches to 0.0784 for scenario I and III, and 0.056 for scenario II and VI, respectively, by the years 2011. Fig. 3 simulates the population of Singapore generated from the model for BS, and scenario I, II, III and VI.

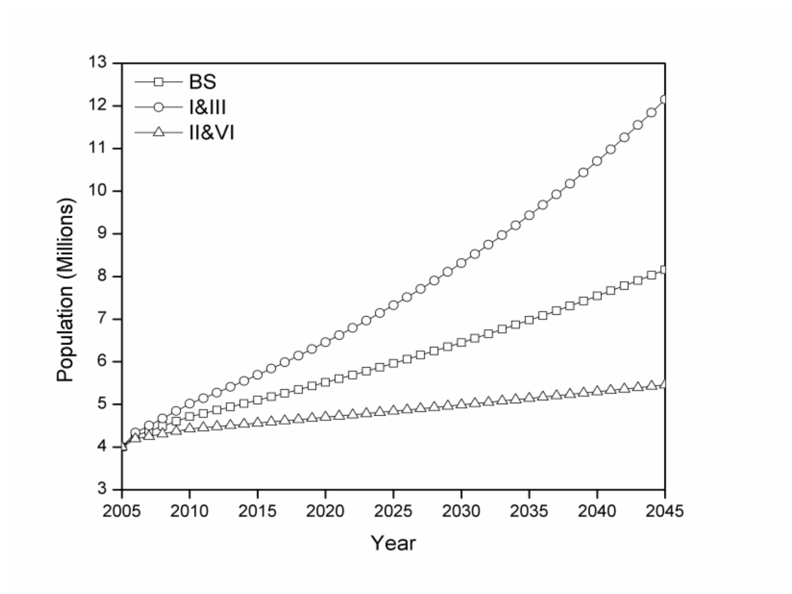

Fig. 3. Projections for the population of Singapore under the baseline scenario (BS), scenario I, II, III and VI.

5. SENSITIVITY ANALYSIS

Sensitivity analysis basically reflects whether minor changes in model parameters can cause any major difference in the performance of model. Only when the robustness of the model is guaranteed, it can be used to make policy (Mohapatra et al., 1994). Since the total MSW generation is highly dependent on the total population and GDP, the sensitivity of the model is influenced from the following parameters:

5.1 Impact of population on MSW generation

Population is considered to be a significant influence on domestic waste generation. It is evident from Fig. 3 that the population of Singapore will increase to 8.15 million for the baseline scenario, while it will dramatically raise to 12 million in scenario I and III by the year of 2045.

5.2 Impact of GDP on MSW generation

The impact of GDP on industrial waste generation was tested by raising the GDP growth rate from 0.0489 to 0.05868 for the year of 2005 and onwards. Fig. 4 indicates that a slight increase in GDP will contribute to the increasing number of MSW generated as shown by the baseline and scenario I, II, III and VI.

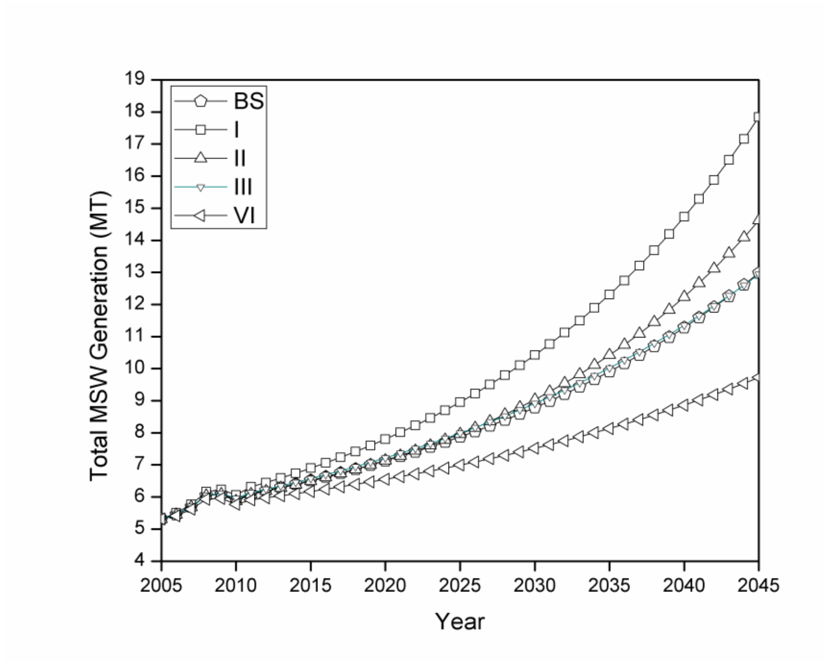

Fig. 4. Sensitivity of the model to different GDP growth rate.

6. RESULTS AND DISCUSSION

The results obtained by modeling the different scenarios are discussed here to ascertain the impact on total population, total MSW generation, landfill capacity, waste disposal and disposal cost (Baseline scenario, Scenario I with high economic growth rate and slow population growth rate, Scenario II with high economic growth rate and high population growth rate, Scenario III with low economic growth rate and high population growth rate, Scenario IV with low economic growth rate and slow population growth rate). After entire analysis of the different scenarios, a suitable solution can be received on best strategy that should not only protect the environment but also it should not inhibit the growth of the economy. Trends are evaluated for a time period of 40 years staring from 2005.

6.1 Total MSW generation

The solid waste in Singapore is classified into three main categories, which are domestic refuse, industrial refuse and institutional refuse. From 1980 to 1987, the institutional solid waste portion increased from 94 thousand tonnes to 292 thousand tonnes, while in the year 1999 and onwards due to the waste recycling, the amount decreased to approximately 6 thousand tonnes. In this paper, because of the small fraction of institutional waste generation compared to the large amount of total MSW generation, the assumption of zero institutional waste was made in order to focus on the main issues.

Fig. 5 shows the industrial GDP variation in all five scenarios. The size of population and economy growth are the two main factors that great influence the total MSW generation. In scenario I and III, the results show that when the population birth rate is the same, the variation amount of total MSW generation is contributed to the variation of industrial GDP growth rate. In scenario II and VI, when the industrial GDP condition is not altered, the increased number of total MSW generation is mainly due to the population size.

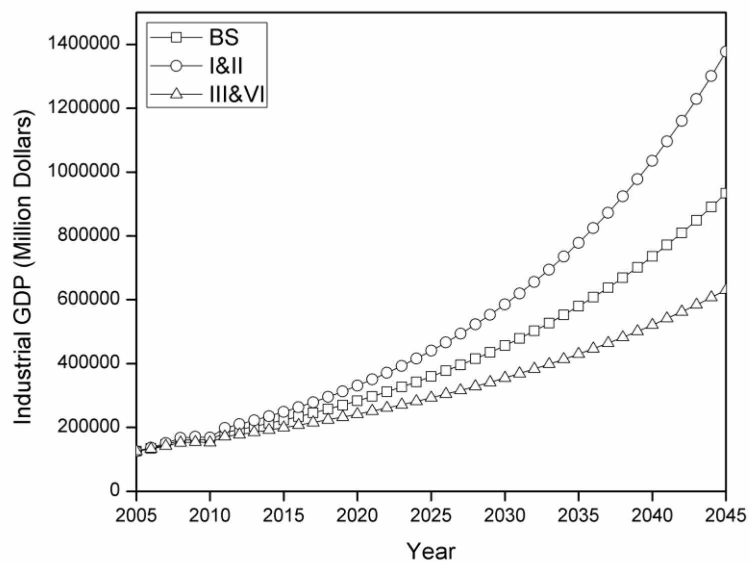

Fig. 5. Industrial GDP in Singapore under baseline scenario (BS), scenario I, II, III and VI.

Fig. 6 illustrates the domestic waste disposal, industrial waste disposal and recycling under baseline scenario (BS), scenario I, II, III and VI. As seen in Fig. 5, the total MSW generation is constantly increased over the 40 years. Similarly, the generation of domestic waste and industrial waste also shows increasing trend, although the level of increasing over time are different. In addition, at the year 2045 in Singapore, the total MSW generation will reach 13 million tonnes in the baseline scenario and III, 17.8 million tonnes in scenario I, 14.6 in scenario II, and 9.7 million tonnes in scenario VI.

In terms of the total MSW generation, scenario II is the suitable case, despite the fact that it is not the least MSW generation amount. The reason is that even in the year of 2045, the amount is only 1% higher compared with the baseline case, and the perdicted birth rate is reasonable given the current condition.

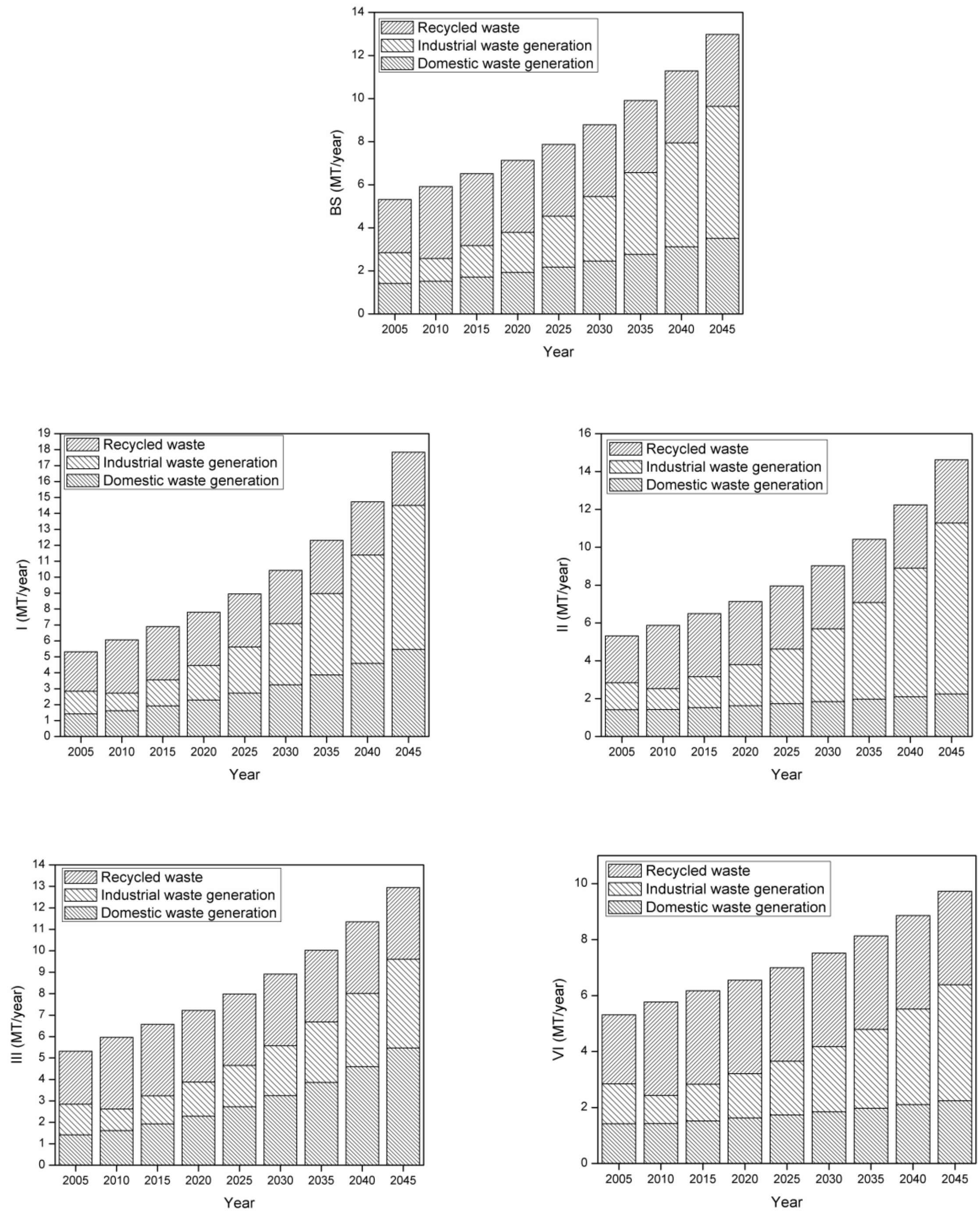

Fig. 6. The domestic waste generation, industrial waste generation and recycling under baseline scenario (BS), scenario I, II, III and VI.

6.2 Landfill capacity and disposal to landfill

The growth of total MSW generation has imposed significant demand on waste management and disposal facilities. Due to the limited land space, landfill is the last option in MSW management decision in Singapore, although it still plays crucial roles in other countries. In Singapore, about 91% of waste collected is incinerated, and the remaining 9% together with the incineration bottom ash is disposed of at Semakau landfill (first off-shore landfill in the world). It was found that despite the fast growing of population size and economy in all of the scenarios, the current landfill capacity could meet the needs until 2040 for scenario II, III and baseline scenario, and 2039 and 2041 for scenario I and VI, respectively. Table 1 provides the classification of landfill capacity and landfill amount under the five scenarios. From these simulation results it is proved that the goal of zero landfill cannot be achieved by reducing only the MSW produced, but should be explored other practical solutions to divert the bottom ash and demolition waste out of the landfill (e.g. land reclamation).

Table 1 Summary of landfill capacity and amount under baseline scenario (BS), scenario I, II, III and VI.

Year	BS		I		II		III		VI	
	Landfill capacity (million tonnes)	Amount to landfill (million tonnes)	Landfill capacity (million tonnes)	Amount to landfill (million tonnes)	Landfill capacity (million tonnes)	Amount to landfill (million tonnes)	Landfill capacity (million tonnes)	Amount to landfill (million tonnes)	Landfill capacity (million tonnes)	Amount to landfill (million tonnes)
2005	63.00	0.29	63.00	0.28	63.00	0.28	63.00	0.29	63.00	0.29
2010	61.11	0.15	61.10	0.15	61.11	0.14	61.11	0.15	61.11	0.14
2015	57.04	0.16	56.98	0.17	57.04	0.16	57.03	0.16	57.10	0.15
2020	50.96	0.18	50.74	0.19	50.98	0.17	50.93	0.18	51.17	0.16
2025	42.70	0.20	42.13	0.21	42.73	0.19	42.62	0.20	43.22	0.17
2030	32.02	0.22	30.78	0.24	32.04	0.22	31.85	0.22	33.11	0.19
2035	18.65	0.25	16.28	0.28	18.60	0.25	18.37	0.25	20.69	0.20
2040	2.26	0.28	**-1.96**	0.33	1.98	0.29	1.81	0.28	5.76	0.22
2045	**-17.58**	0.32	**-24.66**	0.40	**-18.34**	0.35	**-18.20**	0.32	**-11.89**	0.24

6.3 The non-treated waste

Generally, there are three main modes for waste disposal like waste to landfill, waste to incineration plant and waste to recycle plant. In order to achieve no-waste disposal without proper treatment, zero non-treated waste policy should be regulated. Even though Singapore's MSW management system is well developed, a small fraction of MSW is still disposed without proper treatment. Fig. 7 shows the amount of non-treated waste in five scenarios. According to the model projections, the non-treated waste is reaching zero from year of 2005 to 2009, only for scenario IV. On the contrary, scenario I and III have the highest value of non-treated waste, while the scenario II shows the lowest value. In scenario I and III, the quantity of the non-treated waste will not reach 0.1 million tonnes until 2015, while at 2045 the amount will increase to about 0.77 million tonnes. On the contrary, scenario II and IV, the non-treated waste amount will not reach 0.1 million until 2022. The results show that given the current disposal facilities and waste management policy, the amount of non-treated waste will continue to growth from 2009 and onwards.

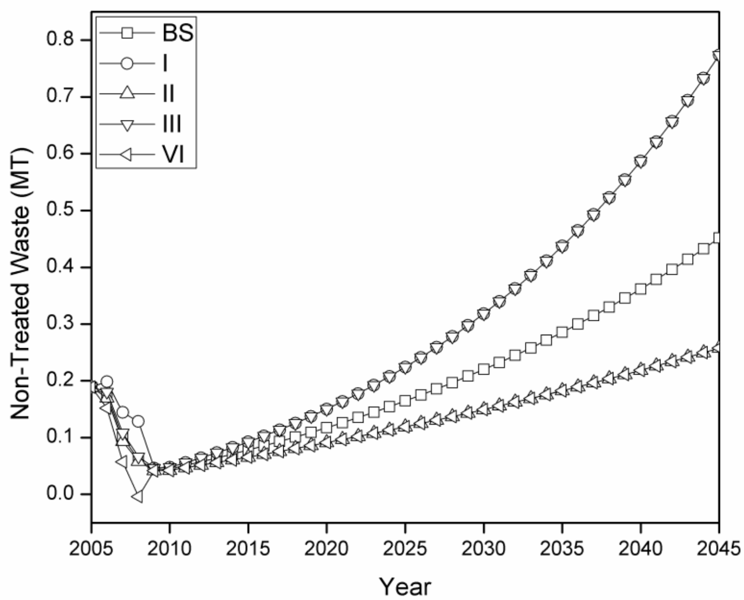

Fig. 7 Amount of non-treated waste in Singapore under baseline scenario (BS), scenario I, II, III and VI.

6.4 Cost

The cost of MSW management includes the cost for waste collection and cost of waste management facilities such as transfer station and landfill. In Singapore, the waste colletion system and disposal is flat rate system, and the fee is paid no matter how much of waste is generated by the user, and traditionally the investment of waste management facilities are historically covered by government. In order to achieve the goal of self-sustainable, a volume based MSW collection system needs to be considered. It will not only financially support the waste business, but more importantly it can raise the environmental sense of the citizens and potentially the waste production may decrease. In addition, the involvement of private companies is another approach that will promote the waste business.

Table 2 illustrates the actual and disposal cost for waste management. It shows that scenario I has the highest cost due to the large amount of MSW generated, while scenario VI has the lowest. The difference between these two costs means that the waste management business is not self-sustained. Hence, the government should either provide funds for waste related companies to survive, or increase the collection and disposal fee in order to support the waste business.

Table 2 Summary of actual cost and dispose cost under baseline scenario (BS), scenario I, II, III and VI.

Year	BS		I		II		III		VI	
	Dispose fee (million $)	Actual cost (million $)	Dispose fee (million $)	Actual cost (million $)	Dispose fee (million $)	Actual cost (million $)	Dispose fee (million $)	Actual cost (million $)	Dispose fee (million $)	Actual cost (million $)
2005	230.2	247.3	230.2	247.3	230.3	247.3	230.3	247.3	230.3	247.3
2010	208.5	223.9	220.5	236.8	205.1	220.3	212.4	228.1	197.0	211.6
2015	257.3	276.4	288.2	309.5	255.7	274.6	262.0	281.4	229.5	246.5
2020	306.9	329.7	361.5	388.2	307.6	330.4	314.0	337.3	260.1	279.4
2025	367.4	394.6	454.8	488.4	374.4	402.2	376.5	404.4	296.1	318.0
2030	441.3	474.0	573.9	616.4	461.0	495.2	451.3	484.8	338.4	363.5
2035	532.0	571.4	726.5	780.3	573.7	616.2	541.2	581.2	388.3	417.0
2040	643.5	691.1	922.5	990.8	720.9	774.3	648.9	697.0	447.3	480.4
2045	781.0	838.8	1174.82	1261.8	913.9	981.6	778.1	835.8	517.2	555.5

4. CONCLUSIONS

This research demonstrates that system dynamics modeling can provide a more comprehensive and sophisticated simulation method for integrated waste management. The multiple feedback relationships (population, economy and waste disposal subsystems) included in the system dynamics model provide different waste management modules under various scenarios. Moreover, the model output graphs and data present a powerful visual and solid way to compare the results of different policy tests and investment options.

The results indicated that the generation of total MSW is expected to increase during the next 40 years influenced by economic growth rate, population and socio-economical level. More specially, the existing landfill capacity is shown to be completely utilized by the year 2040.

By using real data from statistics that are easily available, the SD model presents a practical picture of the next decades in solid wastes management in Singapore. Scenario II is recommended since it covers the requirement for the sustainable growth of economy and environment without exceeding landfill capacity. In addition, in scenario II, other equivalent strategies such as control domestic waste generation and promotion of recycle habit for individuals are plausible ways to ensure waste balance.

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