The Development of a Dynamic Model of Household Waste Recycling in Bangkok, Thailand

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Abstract
Bangkok city currently faces a major problem of landfill shortages, due to an increase amount of wastes generated each year. To properly manage wastes, it is necessary to understand the different characteristics of householders to plan for an effective waste management. This paper utilizes a system dynamics modeling to examine the relationships among key factors influencing household recycling, including the income, population density, and sex. The simulation results reveal that it takes 8 years to sort and recycle all recyclable wastes. It is found that households with medium income recycle maximum amount of wastes, while those with low income recycle the least. The government should, therefore, encourage a recycling campaign in that area to encourage more cooperation in recycling program implementation.

Keywords: household recycling, municipal solid waste, simulation, system dynamic modeling

Introduction
The handling and disposal of household waste in Thailand is a growing concern, as the volume of waste generated continues to increase. According to the Bangkok Metropolitan Administration (2012), the amount of wastes in Bangkok has been increasing 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 is found that 60% of the total wastes can be recycled. Nevertheless, only 12% are recycled, including papers and paperboard, plastic, metal, and glass (Environmental Protection Agency, 2014). This leads to more environmental problems, such as air pollution, water contamination, and landfill shortage (Bangkok Metropolitan Administration, 2012; Kitjakosol, 2013).

Many studies have been conducted to examine key factors influencing household recycling. Jenkins et al. (2000), for example, mentioned that householders living in the community with environmental concern have high intention to recycle. Ittiravivongs (2012), on the other hand, stated that household space affects the decision to recycle. Socio-economic variables, such as population density, household income, and education, are also found having the correlation with the intention to recycle (Sankoh et al., 2012). Afroz et al. (2008), for instance, stated that education is one of the most important factors for the willingness to recycle. They also found that high-income households generate more waste.

Besides, government's involvement in recycling program is crucial in successfully implementing such a program. A number of regulations, such as landfill taxes, surcharges on disposal of recyclable materials, mandated minimum recycled material content in products, and public education program, should be encouraged to enhance the recycling rate (Kovacs, 1988).

In this paper, key factors influencing household recycling are examined, utilizing the system dynamics modeling technique, to plan for an effective recycling program. It is expected that the result results help local community, as well as the government, to better

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understand the key factors influencing the recycling behavior, and plan for an effective recycling program.

The Development of a Dynamic Model of Household Waste Recycling

System Dynamics Modelling

A household waste recycling model is developed using the system dynamics (SD) modeling technique. It is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, and ecological systems. Lyneis (1999), for example, utilized a system dynamics model to understand the causes of industry behavior, and allow early detection of changes in industry structure. Monga (2001) developed a system dynamics performance assessment framework model for the technology development process. Homer and Hirsch (2006) examined the relationships between multiple interacting diseases and risks, the interaction of delivery systems, and diseased using the system dynamics modeling.

A Dynamic Model of Household Waste Recycling

A household waste recycling model is illustrated in Figure 1. It consists of four sub-models, namely the program implementation, the income and population density, the sex, and the simulation results sub-models.

The Program Implementation Sub-Model

The program implementation sub-model (see Figure 2) consists of the benefits and costs of the recycling program implementation. The benefits are calculated from the revenues achieved from selling the glasses, papers, and plastics, while cost depends mainly on the transportation cost, see Equations 1 to 3.

Worthiness_of_Recycling(t) = Worthiness_of_Recycling(t - dt) + (Benefit - Cost)*dt (1)

Benefit = (Glass_Price*Glass_Use) + (Paper_Use*Paper_Price) + (Plastic_Use*Plastic_Price) (2)

Cost = (((Distance*2)*Total_Pickup)/Oil_Consumption)*Oil_Price (3)

The amount of glasses, papers, and plastics used in the benefit calculation depends on the space available of each house type (i.e. single house and condominium), see Equations 4 to 6.

Glass = ((Area_in_Condo + Area_in_house)*0.0839)*Glass_m3_to_Kg (4)

Paper = (((Area_in_Condo + Area_in_house)*0.2976)*Paper_m3_to_Kg)*365 (5)

Plastic = ((Area_in_Condo + Area_in_house)*0.6185)*Plastic_m3_to_Kg (6)

The result of the model gives the value of 0 or 1, with 0 representing no recycling program implementation (when costs are higher than benefits), and 1 is vice versa.

The Income and Population Density Sub-Model

This sub-model, as shown in Figure 3, divides income into three ranges, including low-, medium-, and high-income ranges. Three household areas, namely low-, medium-, and high-density areas, are also considered (see Equations 7 to 9).

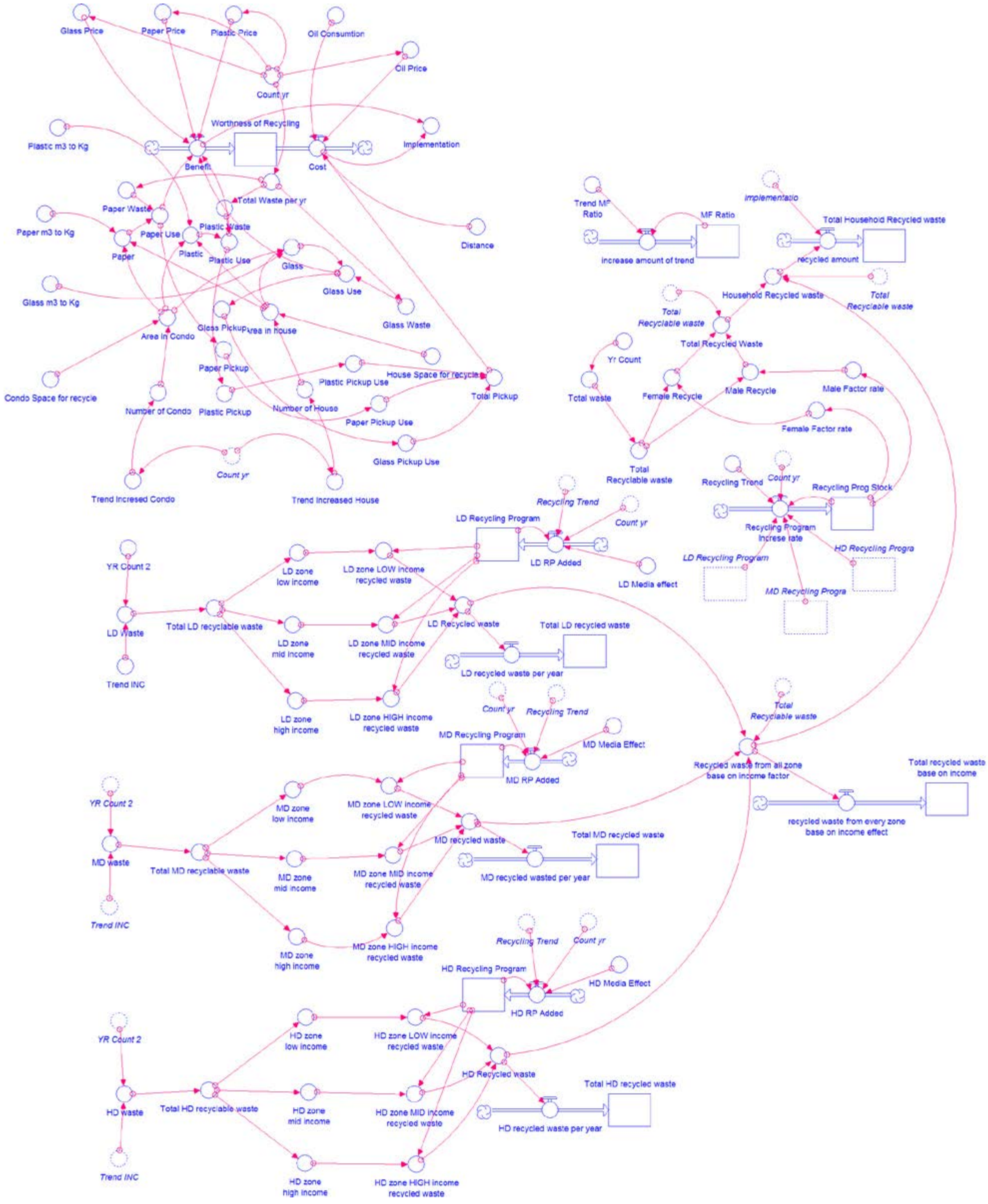

Figure 1. A Dynamic Model of Household Waste Recycling

$$Total\_LD\_recyclable\_waste = ((LD\_Waste/50)*5*365)*0.6 \quad (7)$$

$$Total\_MD\_recyclable\_waste = ((MD\_waste/50)*28*365)*0.6 \quad (8)$$

$$Total\_HD\_recyclable\_waste = ((HD\_waste/50)*17*365)*0.6 \quad (9)$$

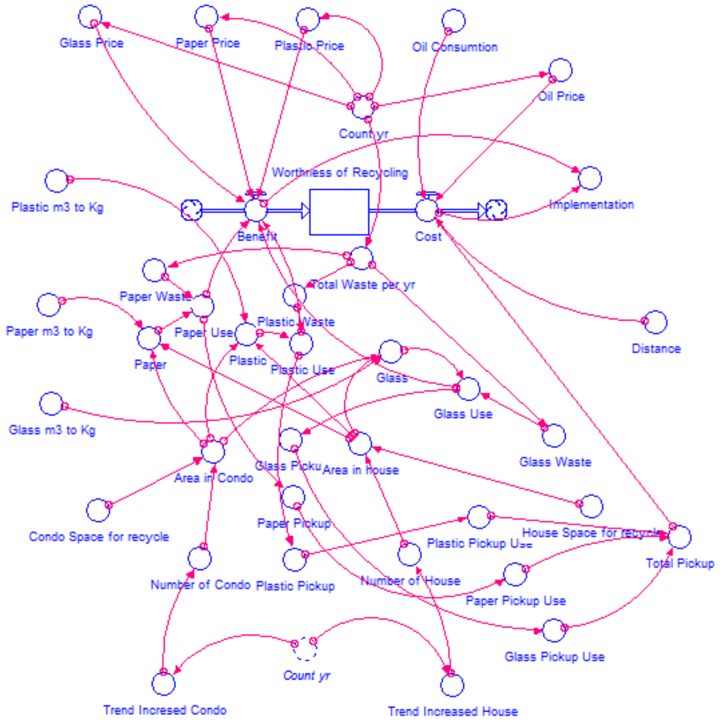

Figure 2. The Implementation Sub-model

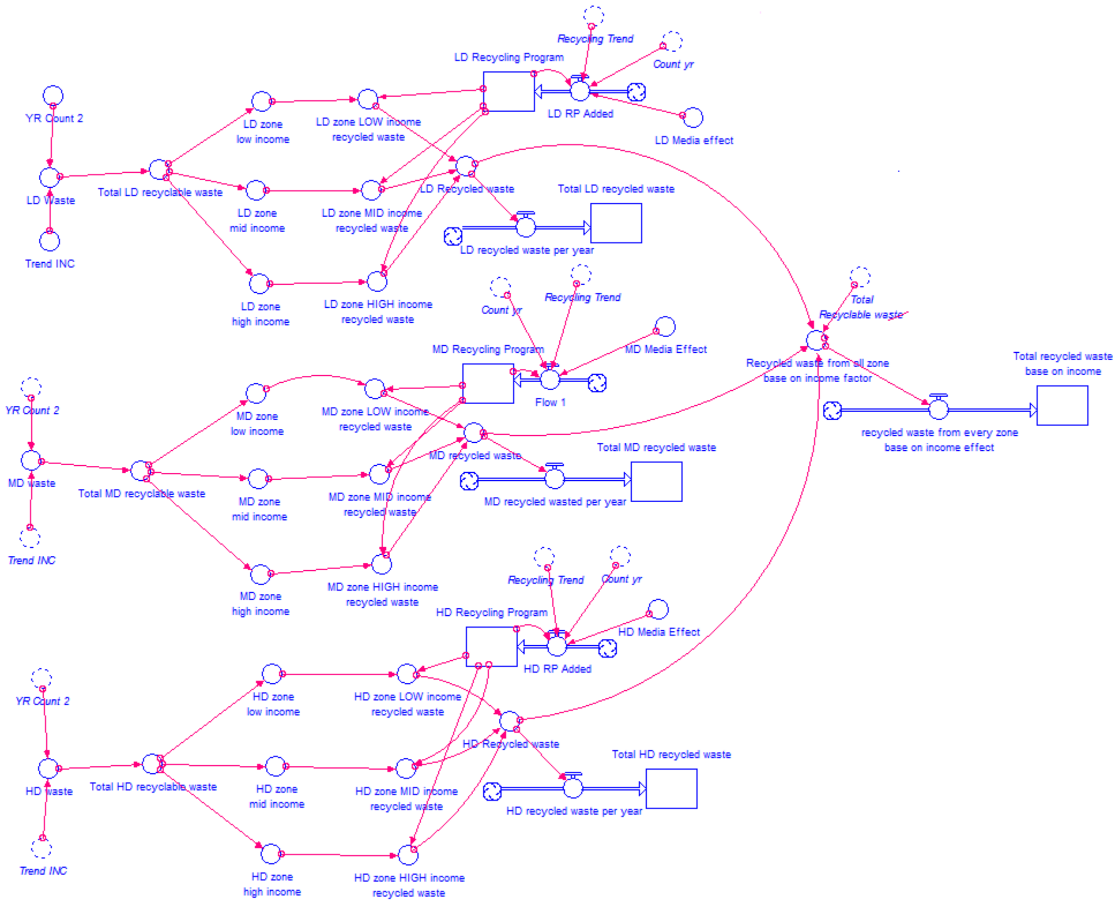

Figure 3. The Income and Population Density Sub-model

The amount of recycled wastes collected from each zone and of the low income range are shown, for example, in Equations 10 to 12.

```
LD_zone_LOW_income_recycled_waste = IF (LD_Recycling_Program*0.1886) >=1 THEN
                                    LD_zone__low_income ELSE LD_zone__low_income
                                    *0.1886*LD_Recycling_Program                    (10)

LD_zone_MID_income_recycled_waste = IF (0.2941*LD_Recycling_Program)>=1 THEN
                                    LD_zone_mid_income ELSE LD_zone_mid_income
                                    *0.2941*LD_Recycling_Program                    (11)

LD_zone_HIGH_income_recycled_waste = IF (0.4298*LD_Recycling_Program)>=1 THEN
                                     LD_zone_high_income ELSE LD_zone_high_income
                                     *0.4298*LD_Recycling_Program                   (12)
```

With the government support in recycle-related activities, such as provision of recycling bins and recycling program promotion through various media channels, the amount of recycled wastes increases, as shown in Equations 13 to 18.

```
HD_Recycling_Program(t) = HD_Recycling_Program(t - dt) + (HD_RP_Added)*dt          (13)

HD_RP_Added = IF (Count_yr=1) THEN ((HD_Media_Effect + 1.38)/2) – 1 ELSE
              HD_Recycling_Program *Recycling_Trend                                (14)

LD_Recycling_Program(t) = LD_Recycling_Program(t - dt) + (LD_RP_Added)*dt          (15)

LD_RP_Added = IF (Count_yr=1) THEN ((LD_Media_effect + 1.38)/2) – 1 ELSE
              LD_Recycling_Program*Recycling_Trend                                 (16)

MD_Recycling_Program(t) = MD_Recycling_Program(t - dt) + (MD_RP_Added)*dt          (17)

MD_RP_Added = IF (Count_yr=1) THEN ((MD_Media_Effect + 1.38)/2) - 1ELSE
              MD_Recycling_Program*Recycling_Trend                                 (18)
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The total amount of wastes collected from each zone, with all income ranges, are as detailed in Equations 19 to 22.

```
HD_Recycled_waste = (HD_zone_HIGH_income_recycled_waste +
                     HD_zone_LOW_income_recycled_waste +
                     HD_zone_MID_income_recycled_waste)/2                          (19)

LD_Recycled_waste = (LD_zone_HIGH_income_recycled_waste +
                     LD_zone_LOW_income_recycled_waste +
                     LD_zone_MID_income_recycled_waste)/2                          (20)

MD_recycled_waste = (MD_zone_HIGH_income_recycled_waste +
                     MD_zone_LOW_income_recycled_waste +
                     MD_zone_MID_income_recycled_waste)/2                          (21)

Recycled_waste_from_all_zone_base_on_income_factor = IF (HD_Recycled_waste + LD_Recycled_waste +
                     MD_recycled_waste) >=Total__Recyclable_waste
                     THEN Total__Recyclable_waste ELSE
                     (HD_Recycled_waste + LD_Recycled_waste +
                     MD_recycled_waste)                                            (22)
```

The Sex Sub-Model

According to Lee and Paik (2010), male and female recycle wastes up to 40% and 20% of the total recyclable wastes, respectively. The recycling rate can, however, be increased with government support in providing recycling knowledge and promoting recycling program through various media channels (Chan, 1998; Kemasiri, 2003).

The sex sub-model is illustrated in Figure 4. The amount of wastes sorted by males and females are explained in Equations 23 to 27, and the total amount of household recycled wastes is shown in Equation 28.

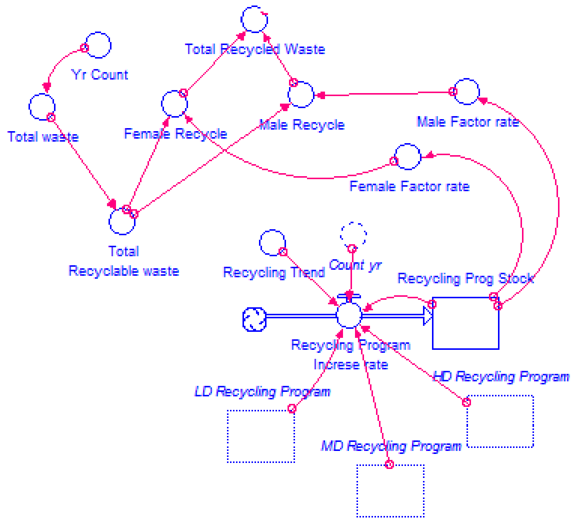

Figure 4. The Sex Sub-model

Male_Recycle = (Male_Factor_rate*Total__Recyclable_waste)2 (23)

Male_Factor_rate = IF (0.4*Recycling_Prog_Stock) >=1 THEN 1 ELSE 0.4*Recycling_Prog_Stock (24)

Female_Recycle = (Female_Factor_rate*Total__Recyclable_waste)/2 (25)

Female_Factor_rate = IF (0.277*Recycling_Prog_Stock) >=1 THEN 1 ELSE 0.277* Recycling_Prog_Stock (26)

Total_Recycled_Waste = IF (Female_Recycle + Male_Recycle) >= Total__Recyclable_waste THEN Total__Recyclable_waste ELSE (Female_Recycle + Male_Recycle) (27)

Household_Recycled_waste = IF ((Recycled_waste_from_all_zone_base_on_income_factor + Total_Recycled_Waste) >= Total__Recyclable_waste) THEN Total__Recyclable_waste ELSE (Recycled_waste_from_all_zone_base_on_income_factor + Total_Recycled_Waste) (28)

Simulation Results

The dynamic model of household waste recycling is simulated. Figures 5 to 7 illustrate graphical results of recycled wastes a three income ranges at different population densities. It is found that the medium- and high-income households recycle more than those with low income. This might be based on the different educational background and recycling knowledge. This is partly confirmed by Afroz et al. (2008) that income and educational background affect the recycled wastes amount.

Figures 8 shows the recycled wastes amount at three different population densities, while Figure 9 displays the graphical results of recycled wastes of males and females. Figure 10 and Table 1 display the household recycled wastes amount.

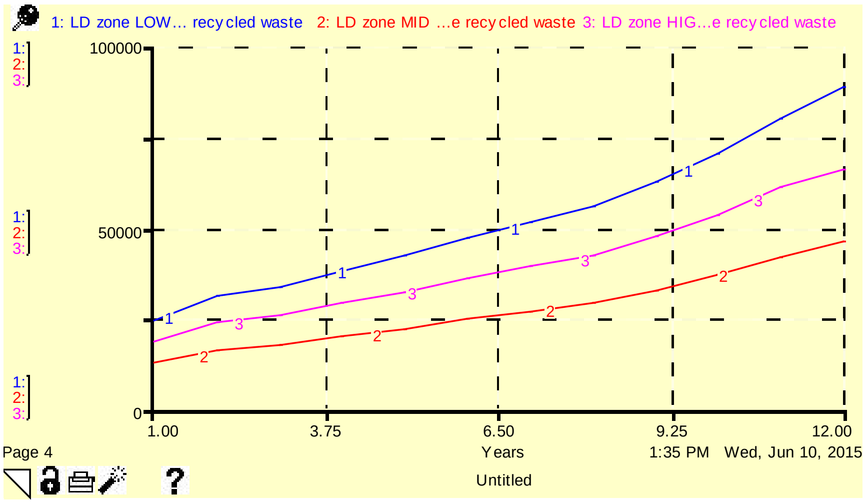

Figure 5. Graphical results of low-income recycled wastes at different population densities

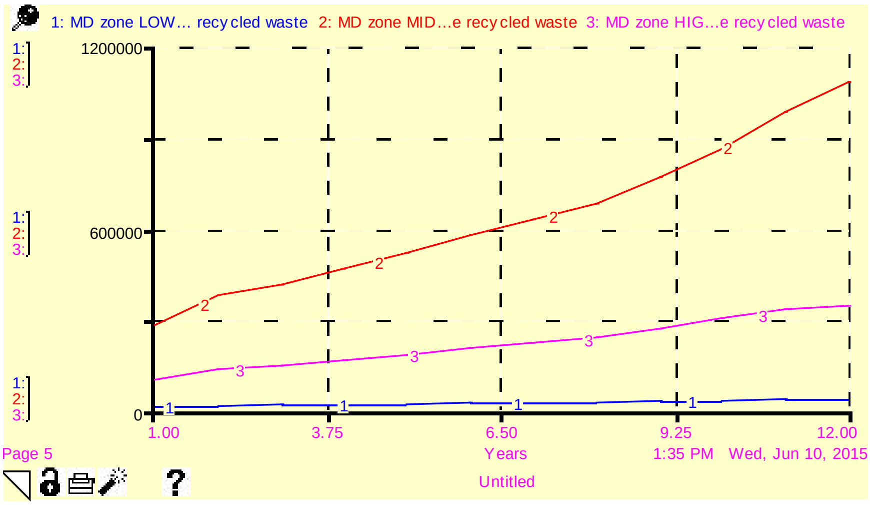

Figure 6. Graphical Results of medium-income recycled wastes at different population densities

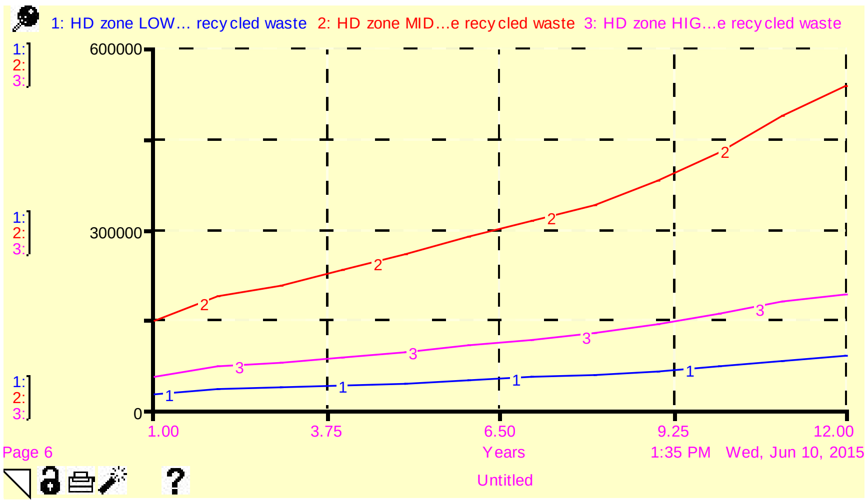

Figure 7. Graphical Results of high-income recycled wastes at different population densities

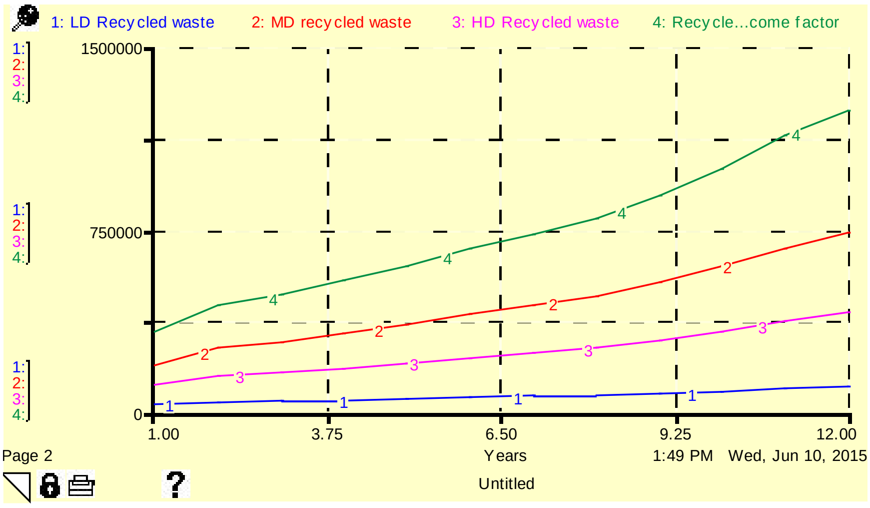

Figure 8. Graphical Results of recycled wastes at three different population densities

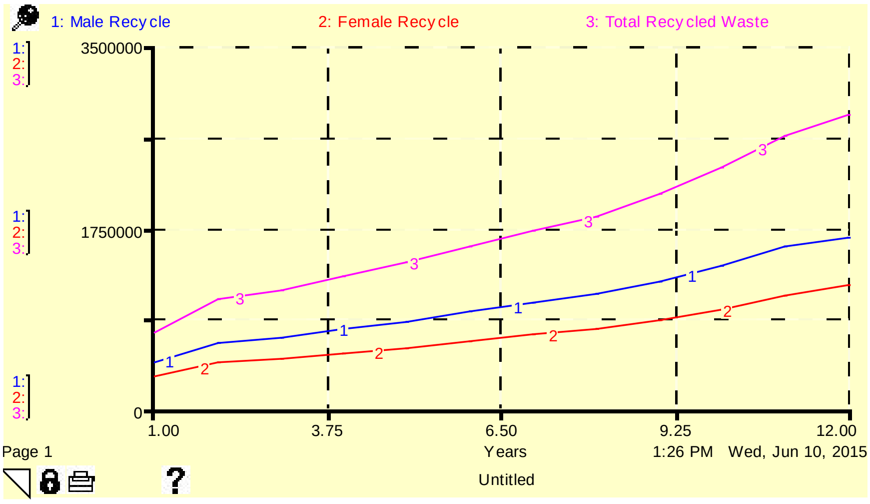

Figure 9. Graphical Results of recycled wastes of males and females

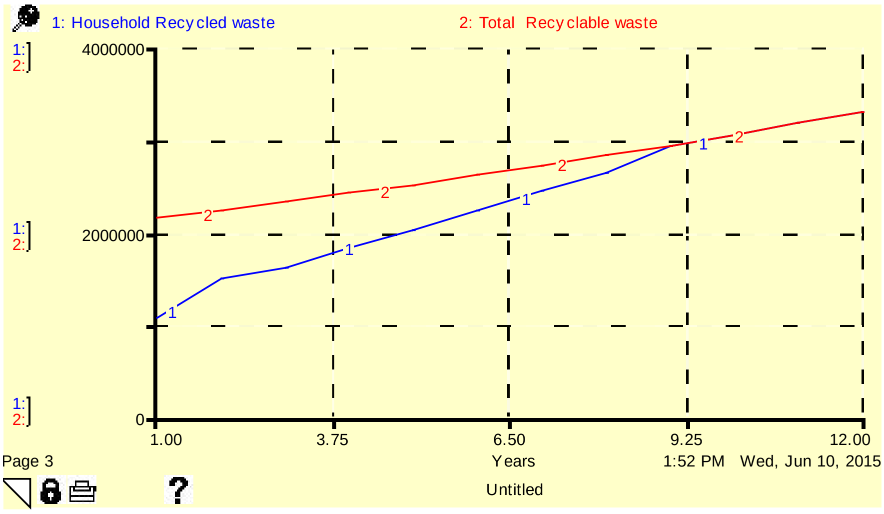

Figure 10. Graphical Results of household recycled and total recyclable wastes

Table 1. Simulation Results of total household recycled wastes

Year	Male Recycled	Female Recycled	Total Recycled	LD Recycled	MD Recycled	HD Recycled	Recycled for All Zones	Household Recycled	Total Recyclable
1	429,240.00	297,248.70	726,488.70	27,679.54	189,540.96	109,167.65	326,388.15	1,052,876.85	2,146,200.00
2	616,045.25	426,611.33	1,042,656.58	35,075.18	260,103.27	142,179.07	437,357.52	1,480,014.11	2,232,048.00
3	669,426.86	463,578.10	1,133,004.97	38,225.21	283,462.61	154,947.88	476,635.71	1,609,640.67	2,321,329.92
4	751,969.55	520,738.91	1,272,708.47	43,146.70	319,958.36	174,897.39	538,002.45	1,810,710.91	2,414,183.12
5	831,787.42	576,012.79	1,407,800.22	47,902.32	355,224.09	194,174.54	597,300.95	2,005,101.17	2,510,750.44
6	923,859.97	639,773.03	1,563,633.00	53,403.65	396,019.69	216,474.45	665,897.79	2,229,530.79	2,611,180.46
7	1,009,169.78	698,850.07	1,708,019.85	58,491.04	433,745.73	237,096.47	729,333.24	2,437,353.09	2,715,627.68
8	1,092,187.62	756,339.93	1,848,527.55	63,435.62	470,412.68	257,139.56	790,987.86	2,639,515.41	2,824,252.78
9	1,223,032.70	846,950.14	2,069,982.84	71,299.17	528,725.58	289,014.87	889,039.63	**2,937,222.90**	**2,937,222.90**
10	1,369,851.75	948,622.34	2,318,474.09	80,139.42	594,281.26	324,849.28	999,269.96	3,054,711.81	3,054,711.81
11	1,555,440.56	1,077,142.59	2,632,583.15	91,352.91	671,194.68	370,303.76	1,132,851.35	3,176,900.28	3,176,900.28
Final	1,651,988.15	1,187,869.81	2,839,857.95	100,376.55	731,195.65	404,979.68	1,236,551.88	3,303,976.30	3,303,976.30

Note: The amount is in tons. LD, MD, and HD are low-, medium-, and high-density areas, respectively.

The results show that in the beginning years, householders cannot recycle all recyclable wastes due to the lack of recycling knowledge. This could be seen from a big gap between total recyclable and household recycled wastes in Figure 11. Once householders gain more experiences, the amount of recycled wastes increase. It takes 8 years for householders to recycle all recyclable wastes (i.e. no gap between total recyclable and household recycled wastes).

From Table 1, it is found that males tend to recycle more than females. It is also found that the amount of wastes sorted in medium-density area are the highest among the three areas. Local municipality should first establish more recycling campaigns in the medium-density area to encourage more cooperation in recycling program implementation. The campaigns should involve males, and clearly state their key responsibilities in the implementation plan. The implementation results should be monitored, and suggestions should be made for the high- and low-density areas to follow.

Conclusion

Waste management is recently an important issue for countries around the world. To properly manage wastes, this paper develops a dynamic model of household waste recycling utilizes a system dynamics modeling. The key factors influencing household recycling, including the income, population density, and sex, are examine to plan for a recycling program implementation.

The simulation results show that it takes 8 years to completely recycle all wastes. It also found that householders, with medium income and live in medium-density area, tend to recycle more wastes. The government could, consequently, use the study results as a guideline to plan for an effective recycling program.

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