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Original Article

Dynamic model for construction and demolition waste recycling in Bangkok, Thailand

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Abstract

With higher numbers of buildings and infrastructures in Bangkok, the number of construction and demolition (C&D) waste increases continuously. These wastes, if not properly managed, will create environmental problems in long term. This study utilizes a system dynamics modeling technique to develop a C&D waste management model. Data and related relationships were collected to develop simulated equations for a dynamic model. The simulation results show that more wastes are sorted and recycled over time when more labors and machines are hired and purchased. Different environmental budgets available to perform the recycling program are also examined, so that the construction industry can effectively plan for its C&D waste management program implementation.

Keywords: C&D waste, recycling, simulation, system dynamics modeling

1. Introduction

With a significantly increase in the population in Bangkok, the numbers of skyscrapers, buildings, and bridges built to support and accommodate Bangkok citizens also increased (Lo & Yeung, 1995). Since higher numbers of buildings and infrastructure has been constructed, the number of construction and demolition (C&D) waste is increasing continuously (Pollution Control Department of Thailand, 2010). The C&D waste comprises of concrete, brick, metal, ceramics, roofing, gypsum, and wood (Sorpimai, 2008). It can be classified into two categories: recyclable (70%) and non-recyclable (30%) wastes. It was, however, found that not all the recyclable wastes were recycled. The leftover is, thus, dumped into landfills, creating environmental problems. The improvement of C&D waste management helps reducing the amount of C&D wastes, thus, decreasing landfill requirement (Hao & Scott, 2001). Table 1 illustrates an increasing trend of C&D waste generation following the increased population in Bangkok, Thailand. As C&D waste is one of the main solid waste generators in Bangkok, its impact on the environment has become an imperative issue to the stakeholders (Hao *et al.*, 2010).

Table 1. Estimated C&D waste amount in Bangkok, Thailand (Sorpimai 2008).

Year	C&D waste (tons)	Per capita per day (kg)
2003	1,189,001	0.30
2004	1,206,496	0.30
2005	1,476,277	0.35
2006	1,501,986	0.36

Past research on C&D waste management has mainly focused on the separate aspects of waste management, including waste reduction, reuse, recycle, and response (Lawson *et al.*, 2001). In this research paper, a simulation model is developed based on a system dynamics methodology to strategically plan for C&D waste management in Bangkok.

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This is performed by incorporating various relationships among key factors affecting a C&D waste management. It is expected that the dynamic model assists the construction industry to better understand about C&D waste, and make a better decision regarding C&D waste management in long term.

2. Research Methodology

Research steps conducted in this study is summarized, as shown in Figure 1. A number of C&D waste-related literatures are reviewed to extract key factors affecting C&D waste management. Data collection are made through primary and secondary sources, including journal papers, text books, annual reports, and interviews, to develop equations for the dynamic model. A dynamic model of C&D waste management is then developed and simulated to achieve the simulation results. Policy analysis is finally performed to examine different policies the construction industry can implement.

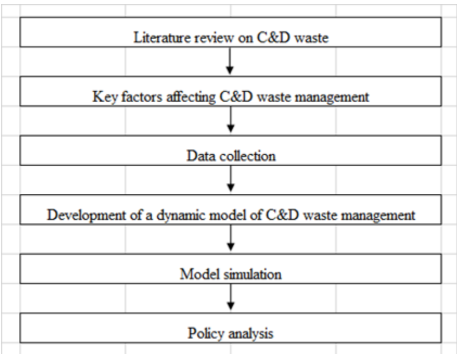

Figure 1. Research steps of this study.

3. Dynamic Model of C&D Waste Management

3.1 System dynamics

System dynamics (SD) is a computer-aided approach to policy analysis and design. It is applied to dynamic problems arising in complex social, managerial, economic, or ecological systems (System Dynamics Society, 2013). It is concerned with creating models or representations of real world systems and studying their dynamics (Forrester, 1994). Richmond (1998) commented that a SD could accept the complexity, nonlinearity, and feedback loop structures that are inherent in physical and non-physical systems, to understand the behaviors of a system. Wolstenholme (1990) added that the SD model requires the analyst to construct the relationships between various state variables and rate variables.

The SD approach has been applied in many industries, including the construction industry. Hao et al. (2010), for example, developed a model, based on a system dynamics approach, to simulate C&D waste management in China. Mohamed and Chinda (2011) investigated the interactions among five key enablers of construction safety culture and their impact on the company's safety goal over a period of time. Giannis et al. (2016) applied a SD model to assess alternative strategies for solid waste management in Singapore, and suggested that a high economic pattern and recycling rate are recommended to satisfy the requirements for economic growth and environmental sustainability, while extending landfill capacity for waste disposal.

In this study, the SD method is used to develop a C&D waste management model to examine the waste recycling amounts and costs associated with the recycling program implementation in 10-year period. The model consists of four sectors, namely the "cost", "labor and machine", "leftover waste", and "recycled waste" sectors. Details of each sector are as followings.

3.2 "Cost" sector

Figure 2 shows the dynamic model of the "ost" sector. The "total cost" is a function of the "cost inflow", which is the summation of the "transportation cost", the "labor cost", the "machine cost", and the "storage cost".

The "transportation cost" (Equation 1) is based on the number of trucks with their fuel costs. A truck used in the model is based on an assumption of a full-truck load capacity. The "labor cost" (Equation 2) depends mainly on the number of labors required in the sorting and recycling processes, the standard wage per person per son (i.e. 300 baht), and number of working days in a year (i.e. 250 days in this study). The number of labors is, however, limited by the available budget the company has to support the environmental-related activities each year (Equation 3). This environmental budget is the maximum budget the company can spend to implement the C&D waste recycling program. It ranges from 1.8–2.4% of the total budget each year (Bureau of the Budget 2011, Strategy and Evaluation Department 2012).

$$\text{Transportation cost} = \text{Fuel\_cost\_to\_recycle\_shop} + \text{Truck\_cost\_to\_recycle\_shop} + \text{Fuel\_and\_truck\_cost\_for\_truck\_to\_landfill} \quad (1)$$

$$\text{Labor cost} = \text{Actual\_number\_of\_labor} * 300 * 250 \quad (2)$$

$$\text{Actual number of labor} = \text{Max (History (Number\_of\_labor\_with\_upper\_bound\_budget, Counter\_year), History (Number\_of\_labor\_with\_upper\_bound\_budget, Counter\_year-1))} \quad (3)$$

The "machine cost" (Equation 4), in the same way, increases as the number of machines used in the sorting process increases. It is based on an average price of a machine, ranging from \$28,620 (858,600 Baht) to \$39,725 (1,191,750 Baht), with an exchange rate of 30 baht per dollar. Based on Data Thailand (2013), 300 construction companies located in Bangkok are medium- to large-size companies, respectively. It is assumed that each company purchases one sorting machine on year 1; number of machines purchased at the beginning of the program implementation is then 30 units (Equation 5). More machines might be purchased in the following years, if needed (Equation 5).

$$\text{Machine cost} = \text{MEAN (858600, 1191750)} * \text{Machine\_purchasing} \quad (4)$$

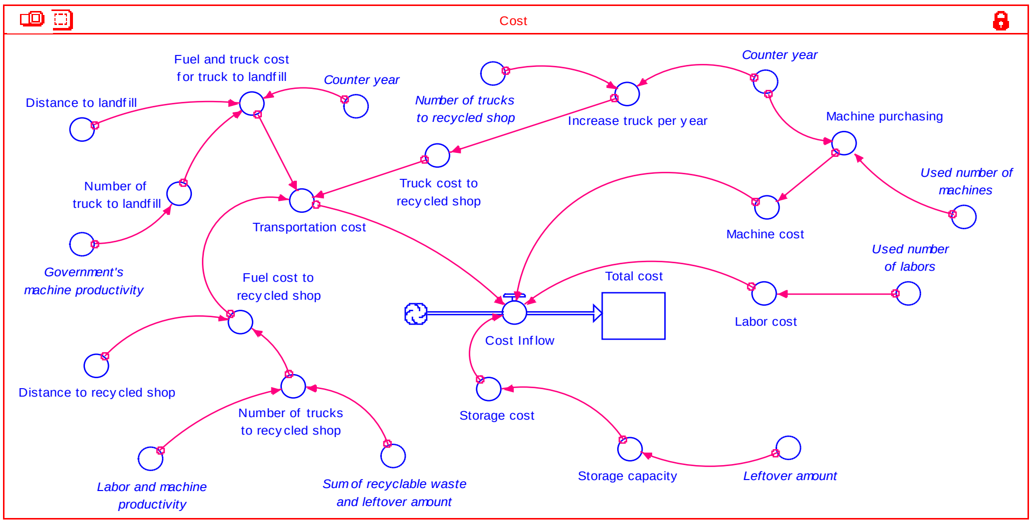

Figure 2. Cost sector.

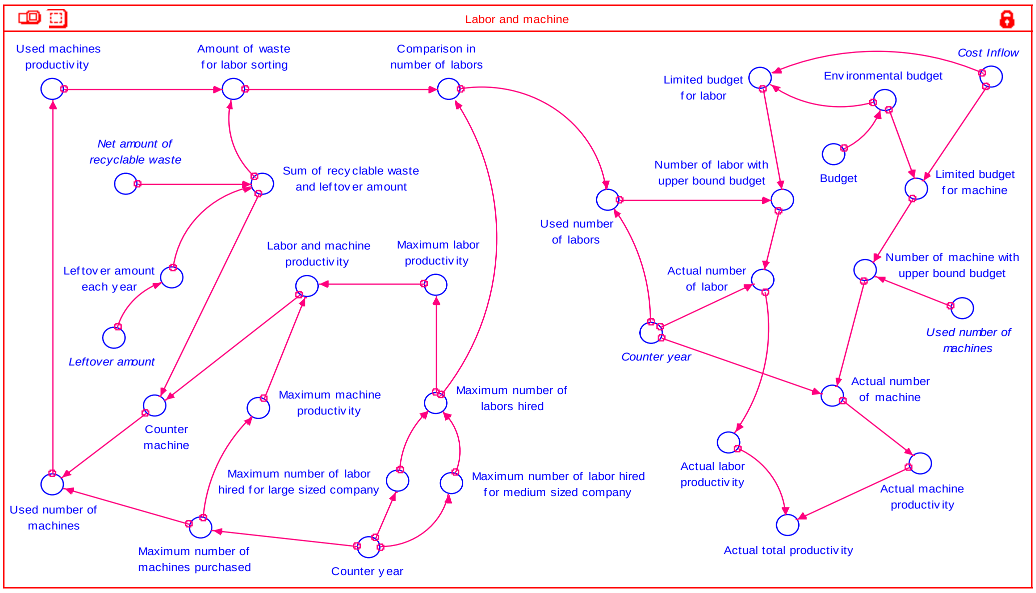

Figure 3. Labor and machine productivity sector.

Machine_purchasing = If (Counter_year = 1) Then (30) Else (History (Used_number_of__machines, Counter_year) – History (Used_number_of__machines, Counter_year - 1)) (5)

Number of labors and machines, however, are not increased when total labor and machine productivity exceeds the amount of C&D wastes to be recycled, indicating that the companies have enough capacity to sort and recycle all the C&D wastes.

The “storage cost” (Equation 6) refers to the cost the construction companies pays to store the C&D wastes before transferring to the next recycling steps. It is calculated at 1,800 Baht/m^2/year (Pantip, 2013). The “DELAY” function is used to refer to leftover wastes in the last years. Finally, the “cost inflow” (Equation 7) is a summation of all involved costs in sorting processes.

Storage cost = DELAY (Storage_capacity *1800, 1, 0) (6)

Cost inflow = Transportation_cost + Labor_cost + Machine_cost + Storage_cost (7)

3.3 “Labor and machine productivity” sector

The “labor and machine productivity” sector (as shown in Figure 3) describes labors and machines used in the sorting and recycling processes. Based on Data Thailand (2013), 200 and 100 construction companies located in Bangkok are medium- and large-sized companies, respectively. It is assumed that each company hires one full time recycling worker each year (or maximum of 300 full time recycling workers hired each year).

Equations 8 and 9 show that the number of labors and machines increase as the recycling program proceeds. These numbers of labors and machines dictate the labor and machine costs the company spends.

Number of labor = MAX (HISTORY (Number_of_labor_with_upper_bound_budget, Counter_year), HISTORY (Number_of_labor_with_upper_bound_budget, Counter_year – 1)) (8)

Number of machine = MAX (HISTORY (Number_of_machine_with_upper_bound_budget, Counter_year), HISTORY (Number_of_machine_with_upper_bound_budget, Counter_year – 1), HISTORY (Number_of_machine_with_upper_bound_budget, Counter_year – 2)) (9)

In Equation 8, the "Number_of_labor_with_upper_bound_budget" is the number of labors the company can hire based on the limited budget. The "MAX" function compares number of labors in the current year with the previous year, then keeps a maximum number for the calculation. Similarly, the "Number_of_machine_with_upper_bound_budget" in Equation 9 is the number of machines the company can purchased based on the limited budget.

Based on Manasakunkit (2013), each labor can sort 0.026 tons of wastes per day. The capacity of waste sorting machine, however, surpasses that of labor, with 4.064 tons of wastes sorted per day (Krause Manufacturing, 2012; Tomra, 2015). Number of working days per year is 250 days. Total productivity can then be calculated by summing labor and machine productivities, Equations 10 to 12.

Labor productivity = Number_of_labor *(0.026*250) (10)

Machine productivity = Number_of_machine *(4.064* 250) (11)

Total productivity = Labor__productivity + Machine_productivity (12)

Figure 4 illustrates the relationship between the recycled waste amount and landfill space. The company's recycled amount depends mainly on total productivity. Once all the recyclable wastes are sorted and recycled, the recyclable wastes to landfill becomes zero, and the productivity becomes constant (i.e. no more labors hired and machines purchased) (Equation 13).

Company's recycled amount = MIN (Net_amount_of_recyclable_waste + Leftover_amount, Total_productivity) (13)

In this study, it is assumed that government supports with two large-sized sorting machines, locating at two main landfills in metropolitan areas, to start the recycling program implementation. This sorting machine has a capacity to sort, on average, 140,000 tons of wastes per year (Alibaba, 2016). The amount of wastes sorted by government's sorting machines, which are 280,000 tons per year in total, are deducted from the total recyclable wastes to achieve the net amount of recyclable wastes (Equation 14).

Net amount of recyclable waste = Total_recyclable_amount – Government's_machine_Productivity (14)

Total recyclable amount, on the other hand, depends mainly on the number of population in Bangkok and the leftover waste amount each year. Registered population in Bangkok is currently at 5.7 million persons (Energy Policy and Planning Office, 2015). Each person generates 0.13 tons of waste per year, with an increasing amount of 0.0018 tons/year; see Equation 15 (Sorpimai, 2008). Based on this waste generation, 70% of them are recyclable waste, see Equation 16.

Amount_of_waste_generation = 0.13 + (Counter_year (1, 11) * 0.0018) (15)

Total recyclable amount = (Amount_of_waste__generation * 0.7) + DELAY (Leftover_amount, 1, 0) (16)

3.4 "Recycled waste amount" sector

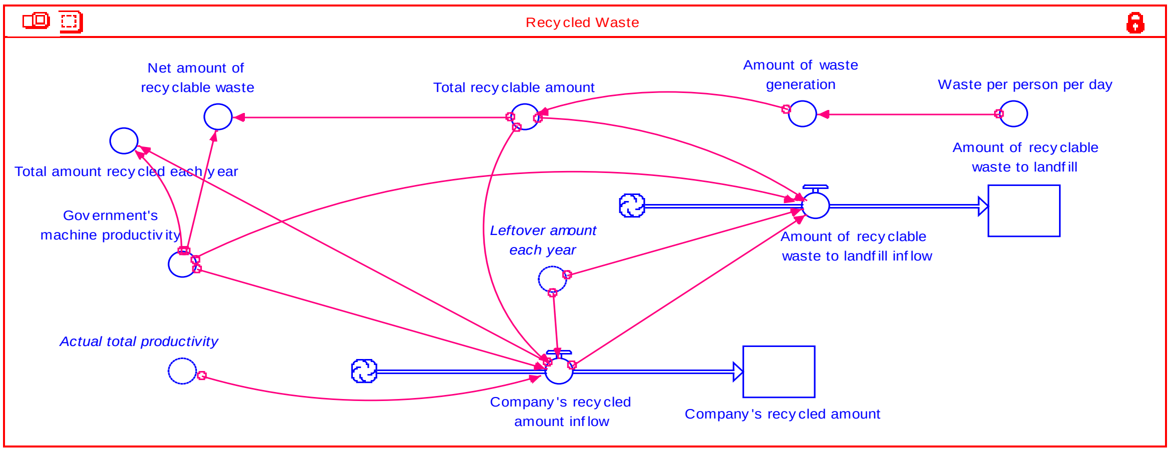

Figure 4. Recycled waste amount sector.

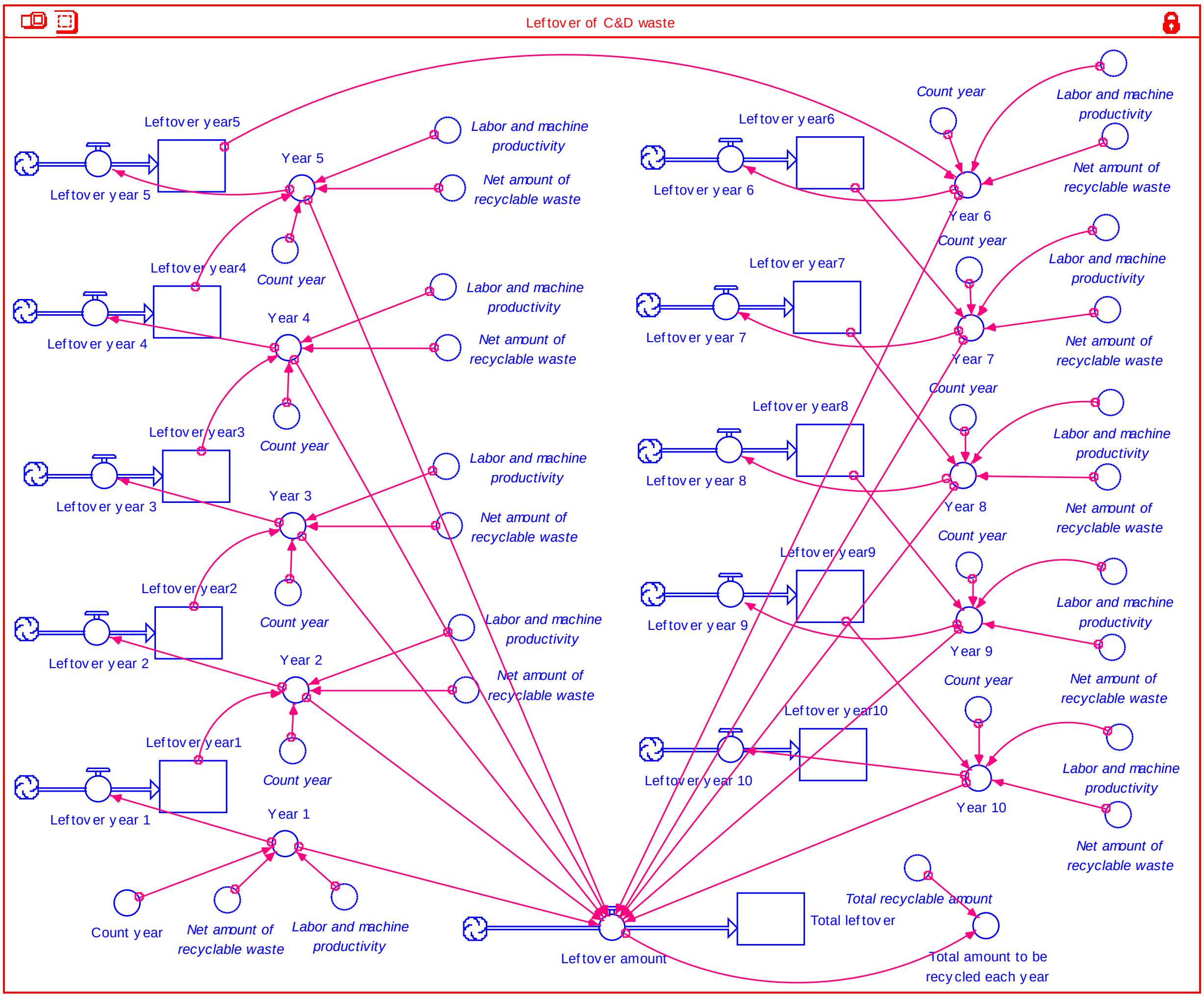

Figure 5. Leftover waste sector.

3.5 "Leftover waste" sector

In the early stage of recycling program, the number of labors and machines are insufficient to sort all recyclable C&D wastes. Consequently, this increases the leftover wastes at the end of the year. These leftover wastes will then be topped up with the amount of wastes generated in the following years, incurring part of the storage cost in Equation 6. Figure 5 shows the "Leftover Waste" sector. The leftover amount at the end of the year is the difference between the net amount of recyclable waste and company's recycled amount (Equations 17 to 19). The leftover amount is then the summation of leftover amount each year for a period of 10 years, Equation 20.

Leftover year 1 = IF (Count_year = 1) THEN (Net_amount_of_recyclable_waste – Company's_recycled_amount) ELSE (0) (17)

Leftover year 2 = IF (Count_year = 2) THEN (IF (Net_amount_of_recyclable_waste + Leftover_year_1 < Company's_recycled_amount) THEN (0) ELSE(Net_amount_of_recyclable_waste + Leftover_year_1 – Company's_recycled_amount)) ELSE (0) (18)

Leftover year 3 = IF (Count_year = 3) THEN (IF (Net_amount_of_recyclable_waste + Leftover_year_2 < Company's_recycled_amount) THEN (0) ELSE (Net_amount_of_recyclable_waste + Leftover_year_2 – Company's_recycled_amount)) ELSE (0) (19)

Leftover amount = Leftover year 1 + Leftover year 2 + Leftover year 3 + Leftover year 4 + Leftover year 5 + Leftover year 6 + Leftover year 7 + Leftover year 8 + Leftover year 9 + Leftover year 10 (20)

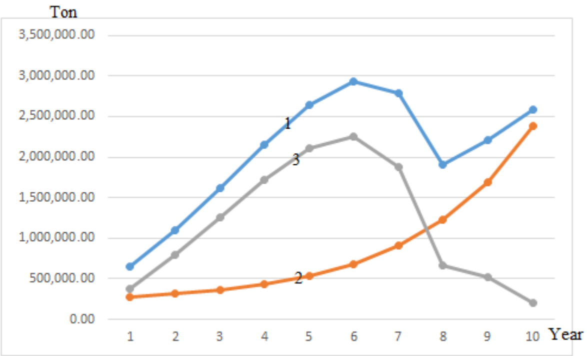

Figure 6. Results of waste amount each year. 1: Net amount of recyclable waste, 2: Company's recycled amount, 3: Leftover amount.

Table 2. Numerical results of waste amount each year (tons).

Year	Net amount of recyclable waste	Company's recycled amount	Leftover amount
1	652,802.50	280,000.00	372,802.50
2	1,101,769.25	312,040.00	789,729.25
3	1,612,243.47	359,320.00	1,252,923.47
4	2,148,435.74	428,290.00	1,720,145.74
5	2,636,703.35	531,160.00	2,105,543.35
6	2,936,650.16	685,465.00	2,251,185.16
7	2,792,394.29	916,922.50	1,875,471.79
8	1,902,978.22	1,233,628.75	669,349.47
9	2,215,780.27	1,693,448.13	522,332.14
10	2,579,605.92	2,383,177.19	196,428.73

4. Simulation Results

The dynamic model of C&D waste management is simulated. The results, as illustrated in Figure 6 and Table 2, show that the amount of recycled wastes increases as time increases, as more labors and machines are hired and used in the sorting process. However, the company is not capable of sorting all recyclable wastes (i.e. amount of wastes initiated each year plus the leftover amount) at the end of year 10, with the leftover waste of 196,428.73 tons (Table 2). This is due to the limited environmental budgets in the early years that result in high amount of leftover wastes.

The costs of program implementation in the early years are low, due to lower number of labors and machines. The cost increases each year as more labors and machines are required to sort all recyclable wastes. It is clear that higher budget available for the recycling program implementation results in higher amount of wastes sorted and recycled. To further examine the effect of the environmental budget on the amount of wastes sorted, different starting environmental budgets are tested with the model through the policy testing analysis.

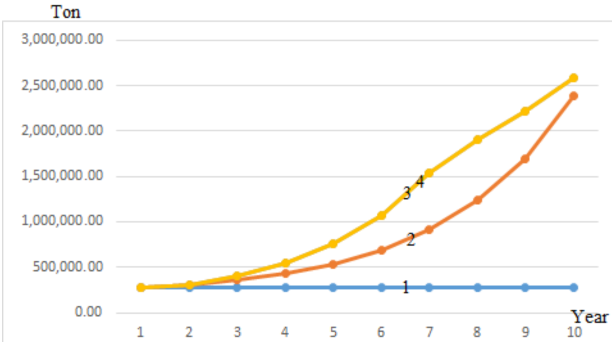

Figure7. Results of company's recycled amount when the environmental budget is changed. 1: Environmental budget of 105 million Baht each year, 2: Environmental budget of 210 million Baht each year, 3: Environmental budget of 315 million Baht each year, 4: Environmental budget of 525 million Baht each year.

5. Policy Analysis with Different Environmental Budgets for Recycling Program Implementation

In the base simulation, the environmental budget available to implement the recycling program is set at around 210 million Baht per year (Bureau of the Budget, 2011). However, this budget might not be constant for all the companies. In the policy analysis, therefore, the environmental budget is changed from the lowest of 105 million Baht to the highest of 840 million Baht. This reflects the situation where the available budget to implement recycling program varies, and that the number of labors the companies can hired, and the number of machines the companies can purchased, must be adjusted.

The dynamic model is run with four possible scenarios: the environmental budgets of 105 (lowest budget), 210, 315, and 525 (highest budget) million Baht, respectively. The simulation results are illustrated in Figure 7 and Table 3. It is observed that when the 105 million Baht of environmental budget is available, the company can recycle a maximum of 280,000 tons each year due to the insufficient budget to hire and purchase more labors and machines, respectively. When the environmental budget is added to a total of 210 million Baht, the company can recycle a maximum of 2,383,177.19 tons at the end of year 10. This, however, does not cover all the recyclable and leftover wastes amount needed to be recycled.

The results show that the company can sort all the recyclable wastes in year 8 when the environmental budget of 315 million Baht is available. On years 9 and 10, the company's recycled waste amount equals to the net amount of recyclable waste, with no leftover amount. From year 8 onwards, the environmental budgets of 420 and 525 million Baht surpasses the total cost spent for the sorting processes. Some budget can then be transferred from the sorting activities to other related activities.

5. Conclusions

As one of the industries with high waste generation, the construction industry needs to effectively plan for the

Table 3. Numerical results of company's recycled amount when the environmental budget is changed (tons unit).

Year	Net amount of recyclable waste (Tons)	Company's recycled amount with different environmental budget (tons)				
		105 million Baht	210 million Baht	315 million Baht	420 million Baht	525 million Baht
1	652,802.50	280,000.00	280,000.00	280,000.00	280,000.00	280,000.00
2	1,101,769.25	280,000.00	312,040.00	312,040.00	312,040.00	312,040.00
3	1,612,243.47	280,000.00	359,320.00	408,550.00	408,550.00	408,550.00
4	2,148,435.74	280,000.00	428,290.00	550,780.00	550,780.00	625,990.00
5	2,636,703.35	280,000.00	531,160.00	758,860.00	758,860.00	946,300.00
6	2,936,650.16	280,000.00	685,465.00	1,067,470.00	1,067,470.00	1,415,065.00
7	2,792,394.29	280,000.00	916,922.50	1,530,385.00	1,530,385.00	2,109,437.50
8	1,902,978.22	280,000.00	1,233,628.75	1,902,978.22	1,902,978.22	1,902,978.22
9	2,215,780.27	280,000.00	1,693,448.13	2,215,780.27	2,215,780.27	2,215,780.27
10	2,579,605.92	280,000.00	2,383,177.19	2,579,605.92	2,579,605.92	2,579,605.92

C&D waste management program implementation to mitigate the environmental problems, and lengthen the landfill spaces. This paper develops a dynamic model of C&D waste management with key factors, including the labor and machine productivity, the leftover waste, and the cost of program implementation. The amount of wastes sorted mainly depends on the labors and sorting machines; these two factors incur major cost of program implementation.

The simulation shows that at the beginning years, the companies have less labor and machine productivity, and that the leftover waste amount increases. With more environmental budget available, more labors and machines are hired and purchased, resulting in more wastes sorted. The policy testing is also performed, and the results reveal that with the budget of around 315 million baht, the company can sort and recycle all recyclable wastes at the end of year 10. It can be seen that the knowledge of labors is crucial in effectively implementing waste management program. To enhance the sorting capacity, the specific C&D waste sorting machine is needed. The government should support, if possible, more sorting machines to encourage the program implementation in long term.

The developed dynamic model assists construction companies in planning for their recycling program implementation. A number of policies could be performed with the model to plan the most effective program implementation within a planned time frame. The dynamic model of C&D waste management is developed based on primary and secondary data in Bangkok, Thailand. To apply the model in other countries, these data should be adjusted.

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