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Dynamic simulation analysis of a construction and demolition waste management model under penalty and subsidy mechanisms

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ABSTRACT

The purpose of this study is to address the problems associated with construction and demolition waste management, also known as “nowhere to dump”. Where the ratio of recycled and reused waste is lower, the paper introduced a penalty and subsidy mechanism and established a new model. Firstly, the system dynamics approach was used to calculate a reasonable penalty range. Secondly, the simulation results demonstrated that the original model needed to introduce a subsidy to encourage recycling and reusing materials in order to improve it; sensitivity analysis was conducted to acquire a reasonable value for this subsidy under a different combination of conditions. Finally, through simulation and analysis for different combinations of penalty, waste disposal charges (WDC), and subsidy scenarios, we arrived at the following main conclusions: (1) Penalties can greatly reduce the amount of illegally dumped waste (AIDW). (2) Subsidies can vastly increase the amount of recycled and reused waste (ARRW), for example, the simulation results showed the ARRW increase by approximately 310.41% in 2020 when the subsidy is equal to 40 yuan/t. Thus, this study concludes that some penalty, WDC, and subsidy combination schemes can effectively alleviate the problems associated with construction and demolition waste management.

1. Introduction

With China's rapid development, construction and demolition (C&D) waste has become a serious environmental problem (Xiao et al., 2016). According to statistics provided by the Chinese Construction Waste Recycling Industry Development Report 2014, with the amount of C&D generated waste (AGW) at more than 1.5 billion t, the ratio of recycled & reused waste is only approximately 5%. Shenzhen's 2014 AGW, alone, reached 30 M m^3. The problem of “nowhere to dump” is not exclusive to Shenzhen, but is occurring in Beijing, Nanjing, and Jinan as well. For example, Beijing had more than 3700 construction sites across the city in 2015; that means a steady stream of waste residue was being produced. But with the intensification of urban construction, it is becoming increasingly difficult to find an appropriate site for the large volume of construction waste.

To this end, this study proposes some improved schemes based on the system dynamics (SD) approach. Some relatively satisfactory optimization solutions were proposed after conducting simulations and testing for different penalty, waste disposal charges (WDC), and subsidy combination scenarios with the aim to not only improve the ratio of recycled and reused waste, but also effectively relieve the problem of “nowhere to dump.”

Qualitative analysis has been used to examine waste generation rates (Lu et al., 2011), environmental performance (Dahlbo et al., 2015; Zambrana-Vasquez et al., 2016), sorting on-site (Yuan et al., 2013), and demolition waste generation (Chen and Lu, 2017). Ding and Xiao (2014) estimated the quantification and composition of building-related C&D waste. In C&D waste management, SD has the following applications: simulation model (Hao et al., 2007), recycling center (Zhao et al., 2011; Tam et al., 2014), construction waste minimization (Wang et al., 2015), environmental performance (Ye et al., 2012; Ding et al., 2016) and social performance (Yuan and Wang, 2013). Yuan and Wang (2014) established a C&D waste management model based on the SD method, and studied the effects of the AGW, the amount of C&D landfill waste (ALW), the amount of illegally dumped waste (AIDW), and the amount of recycled and reused waste (ARRW) under different WDC; however, they used only a one-time 3000 yuan penalty fee and did not study it any further. On this basis, this paper introduced two variables of

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penalty and subsidy to improve it. To this end, we focused on the following problems.

- Sensitivity analysis of the main variables was conducted to determine reasonable scopes of penalties and subsidies.
- Dynamic simulation and policy analysis of the combination scenarios were conducted in order to select the relative optimization combinations.
- Relatively satisfactory solutions are provided to relieve the problem of "nowhere to dump" in Shenzhen.

2. Methods and data sources

2.1. Data sources in the quantification of main variables

Data sources include interview and questionnaire surveys, a literature review, and official statistics. Official statistics are sourced from statistical yearbooks and meeting reports. Some auxiliary variables, usually from interviews and questionnaire surveys, are used because the nature of the problem is integral non-linear, thus there are many control variables and the complexity is high.

(1) Official statistical data such as "Shenzhen Statistical Yearbook 2015" **(Method for quantification: Q1)**

In 2007, the total amount of C&D waste generation in Shenzhen was approximately 9.5 M m^3, and in 2014, it was around 30 M m^3. According to Yuan and Wang (2014), if the density of the generated waste is 1.5 t/m^3, it is assumed that the ratio of waste illegally dumped in 2007 was 2%; hence, the initial value of AGW would be 14.25 M t, and the initial value of the AIDW, ALW, and ARRW would be approximately equal to 0.285, 9.975, and 3.99 M t.

(2) Existing literature **(Method for quantification: Q2)**

For example, the ratio of C&D waste recycling is equal to 28% (Yuan and Wang, 2013), WDC = 80 yuan/t (Ding et al., 2016; Yuan and Wang, 2014). Unit cost of transportation1 = 30 yuan/t, unit cost of transportation2 = 55 yuan/t (Wang and Yuan, 2009; Zhao et al., 2011; Ding et al., 2016), etc.

(3) Estimated value including interview and questionnaire survey **(Method for quantification: Q3)**

Definition 1. Model $GM(1,1,t^{\alpha})$ (Guo et al., 2014)

Assuming that

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\right)$$

is a sequence of raw data, and

$$X^{(1)} = \left(x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\right)$$

is its accumulation generated sequence (1-AGO), where

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), k = 1, 2, \ldots, n.$$

Then

$$x^{(0)}(k) + a\frac{x^{(1)}(k) + x^{(1)}(k-1)}{2} = bk^r + c$$

is defined as the model $GM(1,1,t^{\alpha})$, where, $r \in R^+$, $k = 2, 3, \ldots, n$.

In addition,

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = bt^r + c$$

is referred to a whitenization equation for the model $GM(1,1,t^{\alpha})$.

Assume that $X^{(0)}$ is non-negative, $\widehat{a} = (a,b,c)^T$ is the sequence of parameters in model $GM(1,1,t^{\alpha})$, then the least square estimate sequence of the model $GM(1,1,t^{\alpha})$ satisfies $\widehat{a} = (a,b,c)^T = (B^TB)^{-1}B^TY$, where

$$\mathbf{B} = \begin{bmatrix} -\frac{x^{(1)}(1) + x^{(1)}(2)}{2} & 2^r & 1 \\ -\frac{x^{(1)}(2) + x^{(1)}(3)}{2} & 3^r & 1 \\ \vdots & \vdots & \vdots \\ -\frac{x^{(1)}(n-1) + x^{(1)}(n)}{2} & n^r & 1 \end{bmatrix}$$

$$\mathbf{Y} = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}$$

Determine the solution of this differential equation,

$$x^{(1)}(t) = be^{-at}\int e^{at}t^r dt + \frac{c}{a}$$

Then, it can be obtained the predicted value

$$\widehat{Y}(k+1) = \widehat{x}^{(0)}(k+1) = \widehat{x}^{(1)}(k+1) - \widehat{x}^{(1)}(k).$$

Definition 2. Qualified verification of residual error (Liu et al., 2014)

Assume that $X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n))$ is a sequence of raw data, and $\widehat{X}^{(0)} = (\widehat{x}^{(0)}(1), \widehat{x}^{(0)}(2), \ldots, \widehat{x}^{(0)}(n))$ is its simulation sequence of the prediction model.

$$\begin{aligned} \varepsilon^{(0)} &= (\varepsilon(1), \varepsilon(2), \ldots, \varepsilon(n)) \\ &= \left(x^{(0)}(1) - \widehat{x}^{(0)}(1), x^{(0)}(2) - \widehat{x}^{(0)}(2), \ldots, x^{(0)}(n) - \widehat{x}^{(0)}(n)\right) \end{aligned}$$

is its residual error sequence.

$$\Delta = \left\{ \left|\frac{\varepsilon(1)}{x^{(0)}(1)}\right|, \left|\frac{\varepsilon(2)}{x^{(0)}(2)}\right|, \ldots, \left|\frac{\varepsilon(n)}{x^{(0)}(n)}\right| \right\} = \{\Delta_k\}_1^n$$

is its relative error sequence.

(a) When $k \leq n$, $\Delta = \left|\frac{\varepsilon(k)}{x^{(0)}(k)}\right|$ is called k-simulation relative error, $\overline{\Delta} = \frac{1}{n}\sum_{k=1}^{n}\Delta_k$ is called the average relative error.

(b) $1 - \overline{\Delta}$ is called the average relative precision, $1 - \Delta_k$ is called k-simulation precision, $k = 1, 2, \ldots, n$.