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A System Dynamics Approach to Determine Construction Waste Disposal Charge: A Hong Kong Case Study

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Abstract

Research efforts have been paid extensively recently in construction and demolition (C&D) waste management. Waste disposal charging scheme is found to be an effective tool in achieving waste reduction and minimizing environmental burden, which has adopted globally. However, the determination of waste disposal charging fee (WDCF) was mostly found to achieve full-cost recovery at the present state, rather than forecasted the future need. Consequently, limited attention has received in investigating the system structure in WDCF determination. This study aims at addressing the research gap through developing a generic system structure in determining an optimum WDCF, and elaborating dynamic relationships between social and economic factors and their effect in determining an optimum WDCF. This study integrates quantitative and qualitative factors that are collected from literatures and questionnaire survey to construct a comprehensive system dynamics (SD) model. The model is validated with historical data collected from Hong Kong. Two sets of policy scenario analysis are conducted, which includes comparison on the effect of the newly revised WDCF with the original charges, and determination of the optimum range of WDCF. The simulation results indicates that the newly revised WDCF is ineffective to achieve C&D waste reduction in the long run, which is not a sustainable policy strategy. To achieve significant waste reduction, the optimum increment percentage on original landfill and public fill charges should not exceed 250% and 400%, respectively. The model developed serves as a scientific approach for decision-makers to better grasp the architecture in the complex system of C&D waste management.

Keywords: waste disposal charging fee (WDCF); waste management; construction and demolition waste; system dynamics

1. Introduction

Globally, construction and demolition (C&D) waste is the key contributor to the overall waste composition (Poon, 2007; Wang et al., 2016). Available land spaces have been inadequate to meet the growing demand on housing (McKenzie, et. al., 2010) and other uses such as landfilling (HK EPD, 2005). In the case of Hong Kong, a charging scheme has come into operation in 2005 and revised in 2017, which the current charges to landfills and public fill are HKD$200/t (USD$26/t) and HKD$71/t (USD$9/t), respectively (HK EPD, 2017a). Compared to other Asian and European cities, Korea has proposed at a level of USD$9- 27/t for industrial waste (The Korea Bizwire, 2017), while the United Kingdom has maintained a standard rate of USD$117/t for active waste and USD$4/t for inactive waste (HMSO, 1996). High waste tax in other jurisdictions demonstrated a significant level on C&D waste reduction. High level of landfill taxes in Denmark (USD$51/t) and the Netherlands (USD$97/t) demonstrated a low dependency on landfill and a high level of waste recovery (Integrated Skills LTD, 2004). The increasing need of research effort is indispensable to alievate burden on landfills and public fill that cause adverse environmental and social problems. Studies have been focusing on exploring potential impacts of various C&D waste management strategies, such as identifying contributing operational and economic factors to improve on-site management efficiency (Wang, et. al., 2010), and understanding the importance of recycling in urban housing systme with a dynamic material flow approach (Hu, et. al., 2010). The key to successful C&D waste minisation is to implement waste disposal charging fee (WDCF) or landfill tax (Yuan and Wang, 2014). A modest charge would always be part of the set of optimal policy instruments (Calcott and Walls, 2002). With the literature mostly focusing on factors contributing to sustaianble C&D waste management (Dace, et. al., 2014; Marzouk and Azab, 2013) and characterising waste composition (Vivekananda and Nema, 2014), there is limited understanding of the dynamic relationships between social and economic factors that affect WDCF and the reactions on landfills and public fill behaviour.

Recent studies have investigated political, social and economic factors in managing C&D waste through various case studies, highlighted the barrier of an immature and ineffective regulatory environment for C&D waste (Shen and Tam, 2002; Tam, 2008; Yuan, 2017), proposed the negative impact of poor awareness and behaviour on waste management by practitioners (Wu, et. al., 2017), and emphasised a lack of effective financial rewarding and penalising strategy (Chen, et. al., 2002). Despite recent invesitigations on the impacts of WDCF on C&D waste management such as minimising waste generation and lengthening landfill life span (Lu, et. al., 2015; Yuan and Wang, 2014), there is a lack of understanding about the complex feedback relationships between these factors upon the changing social and economic environment over time. Although previous literature have emphasised static one-way causal relationship from WDCF to the community, their relationships should be in the feedback mechanism. It is, therefore, necessary to develop a new platform to examine interrelationships of component in C&D waste management at a dynamic perspective.

The well-established system dynamics (SD) approach has been adopted for visualising and analysing complex dynamic feedback systems with an enhanced understanding in its underlying system behaviour and structure (Perk and Wolstenholme, 1991). Previous research efforts have highlighted the cost and benefits of economic interaction (Naushad, et. al., 2010), sustainability assessment of construction projects (Marzouk and Azab, 2014; Shen, et. al., 2005; Yuan, 2012; Yuan and Wang, 2013), and a comparison between alternatives of C&D waste recycling facilities (Zhao, et. al., 2011). Preliminary study on the determination of WDCF in Shenzhen was conducted (Yuan and Wang, 2014). However, there is a lack of understanding about the community's actual perception and acceptance level on waste regulations, which could not conduct valid comparison with the existing policy. Therefore, there is an imperative need to ascertain an optimum WDCF that can integrate into existing political measures to cultivate favourable managerial strategies in the long run.

This study intended to elucidate if an optimum WDCF would provide the right incentives to market parties and the dynamic relationships between social and economic factors to achieve construction waste reduction at source, which were ill-defined in previous literature, by (i) constructing SD model to relate quantitative and qualitative factors that were collected from literatures and questionnaire survey, (ii) elaborating the effect of the original WDCF to landfills and public fill with the newly revised charges on the behaviour of waste, and (iii) advocating an optimum WDCF that could meet future increase in generated waste and relieve environmental burden of existing waste-related infrastructure. The scope of study was based on the basic logistics structure of waste handling, including generation, landfilling, public filling and recycling.

2. Methods

2.1 Development of SD-based model to determine waste disposal charge

SD was developed by Jay Forrester, and it was used to provide simulations for long-term decision- making analysis in industrial management. It was particularly suitable for complex systems as it could identify and monitor changes within different subsystems and across subsystems. Four major processes are identified in SD system, including identifying essential variables to address problem, constructing major structure unit causal loop diagrams (CLD) to propose dynamic hypothesis, convert key variables relationship into quantitative stock-flow model and validating model with historical data (Chaerul, et. al., 2007). CLD reflects major feedback mechanisms and have two purposes, which are the preliminary sketches of hypothesis during development of SD models, and the simplification of models. As shown in the figure, causal relationships between variables were considered. **(Figure 1)** Positive and negative sign represent the direction of causality. A positive or self- reinforcing loop indicates the change of originating components that strengthen the original process. A negative or balancing loop indicates the response of other components that counteract with the change of the originating component (Hannon and Ruth, 1994).

The first loop (R1) is a negative feedback loop. Within this loop, when the amount of C&D waste landfilled increases, constraints on its landfilling is raised, and leads to an increasing influence on effectiveness of regulation. Subsequently, incentive of waste reduction is enhanced, and leads to a rise in waste decreasing rate that results in less C&D waste generation. Eventually, there will be less amount of C&D waste being landfilled. The second loop (R2) is also a negative feedback loop. When there is an increase in C&D waste generation, there is an enhancement in effectiveness of regulation. So, there will be greater incentive to reduce waste, which results in a higher waste decreasing rate, and produces less C&D waste. The third loop (R3) is a negative feedback loop as well. When there is an increase in C&D waste being public filled, constraints on C&D waste public filling is enhanced, and effectiveness of regulation is raised. As a result, there will be higher incentive for waste reduction, leading to higher waste decreasing rate. Less C&D waste is resulted, and the amount of C&D waste public filled is reduced. The last loop (R4) is a positive feedback loop. When there is an increase in the amount of recycled wastes, there is a positive impact on waste recycling driving factor, and effectiveness of regulation is enhanced. Completeness of waste recycling market is then promoted and leads to a lower waste recycling costs due to a better economic environment of the industry. Ratio of recycled waste is higher and further reduces the amount of recycled waste. **(Figure 2)** Causal loop diagram (CLD) was then constructed through the Stella Architect software package to demonstrate better understanding of the causal relationships among factors. **(Figure 3)** Stock, flow, converter and connector are the major components of CLD. Stock refers to state variables and shows major accumulation within system. Flow indicates the rate of change in stock and shows activities that fill in or drain stock. Converter is intermediate variables. Connector shows the positive and negative information links for cause- effect relationship between stocks (Chaerul, et. al., 2007).

2.2 Quantification of major variables and data collection of qualitative variables

Four major stocks in this system, including the amount of C&D waste generated, amount of C&D waste landfilled, amount of C&D waste public filled and amount of recycled waste, are quantified by obtaining historical statistics from year 2005 to 2015 (HK EPD, 2017b). In 2005, the initial value of the amount of C&D waste generated was 14.16 million t, the amount of C&D waste landfilled and public filled were 2.4 million t and 8.11 million t, and that of the amount of recycled waste was 8.4 million t respectively (HK EPD, 2006) **(Table 1)**.

Effectiveness of regulation execution relies on three major factors, including enforceability, completeness of regulations and effectiveness of supervision. The rating values of these factors were input into the SD model with the range from 0 to 1, with 0 suggesting the worst situation and 1 indicating the best situation. In order to develop state-of-the-art waste management policy, quantitative survey was conducted to investigate initiatives that determine the recycling behaviour with various stakeholders in Hong Kong, including public, government officials and practicitioners in the construction sector. Among all factors, enforceability of regulation was considered the most important factor when formulating C&D recycling policy, followed by effectiveness of supervision and completeness of regulations (Mak, et. al., 2017). Therefore, they are assigned with weightings at 035, 0.33 and 0.31, respectively **(Table 1)**.

An increase in WDCF promotes the incentive for construction site contractors to implement on site waste reduction measures. Therefore, it is assumed that WDCF shows subsequent effects on effectiveness of regulation execution and then influence incentive for waste reduction, which ranges from 0 to 1. In particular, 0 represents the lowest incentive situation while 1 indicates the highest incentive situation. **(Table S1)** It is also predicted that a decrease in the cost of C&D waste recycling would be resulted when recycling activities were encouraged in the industry. So, the maturation of waste recycling market is a factor affecting the cost of recycling and their relationship is illustrated. It is well- recognized that negative interrelations are obtained between ratio of waste being landfilled and its costs, and ratio of waste being public filled and its relative costs. **(Table S1)**

2.3 Model validation

Validity of SD model should be ensured to demonstrate high accuracy of model to determine whether it mimics the real situation well enough for its stated purposes (Forrester, 1961; Forrester and Senge, 1980; Richardson and Pugh, 1981; Zedba, 2002). The model is also crucial to demonstrate high degree of confidence to place in model-based inferences about the real system (Sterman, 2000). Two tests were adopted for structural validation of SD model constructed, which were model behaviour verification test and extreme conditions test (Qudrat-Ullah and Seong, 2010). Behaviour validity of model can be ensured by conducting model behaviour verification test. A number of statistical tests were suggested in the validation literature for comparison with output data from a SD model (for example, Barlas, 1989). On other hand, structural validity of model can be ensured by conducting extreme conditions test, which determines whether the model exhibits a logical behaviour when selected parameters are assigned with extreme values (Forrester and Senge, 1980) It can detect major structural flaws of the model even if it can generate behaviour pattern in high accuracy (Barlas, 1989). To further quantify the statistical significance of two sets of data, Mann-Whitney test were conducted by comparing two independent non-parametric samples. The null hypothesis is that the distributions of both groups are identical. If the P value is smaller than 0.05, null hypothesis can be rejected and that the difference is due to random sampling, and conclude instead that the populations are distinct (Cheung and Klotz, 1997; Nash, 2001) If the P value is greater than 0.05, it can be concluded that there is no statistical differences between the sets of data.

3. Results and Discussion

3.1 Model validation

Simulation results was compared with actual data to verify model behaviour. Empirical data of the annual amount of generated waste from year 2005 to 2015 was collected for model testing, and input as reference data. Simulation data and actual data were then compared.

(Figure 4). As the U value (48) was greater that the U-critical value (31) and the two-tailed P-value (0.44) was greater than 0.05. The null hypothesis could not be rejected. Although it is difficult to conclude that the two unpaired data were identical, the Mann-Whitney test could still confirm that the simulation data and actual data had insignificant statistical differences. Therefore, the behaviour validity of model is confirmed.

Extreme values were assigned to two selected parameters, which were the "Increment % of original $WDCF_1$ change" and "Increment % of original $WDCF_2$ change". **(Figure 5)** The main purpose was to demonstrate how the amount of landfilled waste and the amount of public filled waste would change when extreme values were assigned to $WDCF_{1,2}$. In the model, dependent variables received values greater than zero. Three scenarios were designed for simulation, including scenario 1 (Increment % of original $WDCF_1$ and $WDCF_2$ change= 0, which was the first extreme condition test), scenario 2 (Increment % of original $WDCF_1$ and $WDCF_2$ change= 0.2, which was the base run simulation), and scenario 3 (Increment % of original $WDCF_1$ and $WDCF_2$ change= 100, which was the second extreme conditio test). It was evident that the accumulated amount of landfilled and public filled waste would grow significantly by year 2040. This might due to minimal recycling acitivities implemented by practitioners when there was limited economic or regulatory incentives. When compared to scenario 3, significant reduction on landfilled and public filled waste was observed. By 2040, the amount of landfilled and public filled waste reduced by 71% and 67%, respectively if there was 10000% increment on the original WDCF change. In the base run simulation, there was insignificant reduction on the amount of landfilled and public filled waste, and exhibited a similar trend to scenario 1 in the extreme condition tests. Scenario 2 demonstrated a negative impact on the amount of landfilled waste In comparison with scenario 1 (*i.e.* increase on amount of landfilled waste). **(Figure 5a)** If charges remained at an increment percentage change of 20% on the original charges on waste to landfill and public fill, the amount of C&D waste landfilled, public filled and recycled would increase significantly. By 2040, there would be 46.9 million t of waste to be handled by landfills and 48 million t of waste to be handled by public fills. **(Figure 6)** This indicated that there is an urgent need to amerliorate the present charges on landfill and public landfill to avoid irretrievable situation.

3.2 Policy scenrios analysis

Upon the input of all variables into the model, a series of case studies were conducted and further analyzed. The model was simulated from year 2005 to 2040, a total of 35 years. The major purpose was to investigate how the amount of waste going to landfill, public fill and recycling would respond to changes in the WDCF to landfill and public fill, respectively; thus, the independent variable in the simulation was the increment percentage of original WDCF change.

3.2.1 Simulation result of the effect of the newly revised waste disposal charges

The first section analyzed simulation result of the effect of the newly revised WDCF on landfill and public fill. After the completion of a review of the relevant charges, the Government in 2017 concluded the legislative process to increase the WDCF to landfill and public fill. To achieve full-cost recovery, the landfill charge was increased from HKD$125 t to HKD$200/t and the public fill charge was increased from HKD$27/t to HKD$71/t (HKEPD, 2017a). In order to comprehend the impact of the newly revised WDCF in the long run, the effect on the amount of C&D waste landfilled **(Figure 7a)** and the amount of C&D waste public filled **(Figure 7b)** were compared. When comparing to the original WDCF to landfill (*i.e.* HKD$25/t), there was no obvious reduction in the amount of waste going to landfills by 2040. By year 2022 to 2025, amount of landfilled waste would increase in the range of 2.17% to 2.40%. **(Figure 7a)** When the WDCF was revised to HKD$71/t, it had a more positive impact on the amount of C&D waste public filled. There was 8.8% waste reduction by year 2040, compared with original WDCF (*i.e.* HKD$25/ t). **(Figure 7b)** This may due to an insufficient economic incentives to reduce waste. To relieve stress in landfills and public fill and promote waste reduction at source, it is indispensable for the government to propose new charges in the near future.

3.2.2 Simulation result of determining optimum range of waste disposal charges

As discussed in section 3.1, the base run simulation was set at the level of 0.2. To further determine the optimum range of $WDCF_1$ and $WDCF_2$, 13 additional alternatives of the increment percentage of original WDCF change (*i.e.* 0.7, 0.9, 1.2, 1.5, 2, 2.5, 2.8, 3, 4, 4.5, 4.8, 5 and 6) were designed and simulated. **(Figure S1)** Waste reduction in landfills and public fill could be observed as a general tendency of decline. **(Figure S1a)** Particularly, when the percentage increase was 20%, there would be an average of 2.51% increase in the amount of landfilled waste over the simulation period. When the percentage increased to 70%, a slight waste reduction of 1.93% in landfilled waste could be observed by year 2040. Surprisingly, a significant waste reduction appeared when there was an 120% increase in charges. **(Table 2**) In 2040, there would be a reduction of over 20% of landfilled waste. It is evident by the results that there was a dramatic decrease of landfilled waste if $WDCF_1$ was in the range of HKD$312.5/t (*i.e.* percentage change equals to 150%) to HKD$437.5/t (*i.e.* percentage change equals to 250%) by 2040. The amount of landfilled waste levelled off beyond HKD$437.5/t in 2040. **(Figure 8a)** This reinforced the effectiveness of waste disposal charging scheme in reducing construction waste in Hong Kong (Hao, et. al., 2008), Denmark (Anderson, 1998) and the Netherlands (Bartelings, et. al., 2005). This indicates clearly that from the perspective of landfilled C&D waste reduction, the charges should be in the range of HKD$312.5- 437.5/t.

Changes in WDCF exhibited little impact on the reduction of public filled C&D waste at a lower increment percentage. **(Figure S1b)** When percentage increased from 20% to 150%, the average public filled waste reduction ranged from 1.28% to 5.0%, which showed insignificant waste reduction. When percentage increased beyond 200% till 450%, substantial decrease of public filled waste was observed. In 2040, **t**here would be a reduction of almost 20% public filled waste when the percentage increase on charges raised to 250%. **(Table 2)** To better determine the optimum range of WDCF on public fill, a dramatic reduction of public filled waste in 2040 was observed when charges were in the range of HKD$108/t (*i.e.* percentage change equals to 300%) to HKD$135/t. (*i.e.* percentage change equals to 400%). Unexpectedly, there was a negative impact on the amount of public filled waste when the charges was beyond HKD$149/t, which would increase waste burden on public fill. (**Figure 8b)**

3.2.3 Scenario analysis

In order to analyse the influence of various combinations in landfill and public fill charges on waste generation and recycling, six policy scnerios were then developed. Optimum ranges of landfill charges (*i.e.* $WDCF_1$) selected for further investigation were HKD$312.5/t, HKD$375/t and HKD$437.5/t, while that of public fill charges (*i.e.* $WDCF_2$) would be HKD$108/t and HKD$135/t. Scenario 1 (S1) refers to $WDCF_1$ as HKD$312.5/t and $WDCF_2$ as HKD108/t; Scenario 2 (S2) refers to $WDCF_1$ as HKD$312.5/t and $WDCF_2$ as HKD135/t; Scenario 3 (S3) refers to $WDCF_1$ as HKD$375/t and $WDCF_2$ as HKD108/t; Scenario 4 (S4) refers to $WDCF_1$ as HKD$375/t and $WDCF_2$ as HKD135/t; Scenario 5 (S5) refers to $WDCF_1$ as HKD$437.5/t and $WDCF_2$ as HKD108/t; Scenario 6 (S6) refers to $WDCF_1$ as

HKD$437.5/t and WDCF$_2$ as HKD135/t.

Waste flow to landfills and public fill were compared to suggest the optimum charges that should be implemented in Hong Kong. It is obvious that S1 and S2 both demonstrated minimal reduction impact on the waste flows to landfills and public fill. **(Figure 9)** Steady waste flow could be maintained till year 2030 if S1 or S2 were implemented. Upon the implementation of S1 and S2, waste flow to landfills **(Figure 9a)** and public fill **(Figure 9b)** had an average of 36.2% and 36.7% increase from 2030 to 2040, respectively. Significant reduction in waste flow to landfill could be observed when either S5 or S6 were implemented. Average waste flow from 2017 to 2040 dropped by one-forth, when comparing S4 with S5. **(Figure 9a)** Similarly, waste flow to public fill under S1, S2, S3 and S5 remained at a high level, which was over 10 million tonnes. Significant low level of waste flow was observed upon the implementation of S4 and S6, which had only an average increase of 26.7% and 30.7% from 2017 to 2040. **(Figure 9b)** Based on the above discussion, S6 suggested the optimum scenario to minimise landfilled and public filled waste. It is recommended that the increment percentage on original landfill charges should not exceed 250% (*i.e.* HKD$437.5/t) , while that on public fill charges should below 400% (*i.e.* HKD$135/t) to improve practitioners' awareness and waste minimisation at source.

4. Conclusion

WDCF is always an effective tool in waste reduction strategies. However, the determination of charges was mostly found to achieve full-cost recovery at the present state, rather than forecasted the future need. This study enlightened the community and decision-makers by visualising the basic system structure of an optimum WDCF determination. A SD model considering the actual situation of Hong Kong as a case study, demonstrated a comprehensive analysis on the dynamic feedback relationships of WDCF and C&D waste generation, C&D waste landfilled, C&D waste public filled and recycled C&D waste. The results compared the effect of newly revised WDCF in 2017 with the original charges, little impact on landfilled waste reduction was observed by year 2040. In other words, a higher WDCF is crucial to achieve a better minimising effect on waste going to landfills and public fill. By 2040, over 20% of landfilled and public filled waste could be achieved, which WDCF was at the range of HKD$312.5 to HKD$437.5/t and HKD$108 to HKD$135/t, respectively. The findings from the comparison of six policy scenario analysis revealed that the optimum increment percentage on original landfill and public fill charges should not exceed 250% and 400%, respectively.

Limitations existed in this study. Firstly, the scope of study focused mainly on the impact of WDCF by the four major components in C&D waste management. Other driving factors such as elasticities of charges, availability of waste recycling infrastructure could be investigated and broaden the research scope. Secondly, situation of illegal dumping were excluded as such data was not reported by the government and the amount should be neglectable upon the enforcement of construction waste disposal charging scheme in Hong Kong. The existence of illegal dumping could be take into account in other jurisdictions. To conclude, this study offered a holistic strategic platform and articulated the need of a scientific approach to assist decision-makers implementing a state-of-the-art C&D waste management policies to reduce future uncertainties.

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