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System Dynamic Analysis of Impacts of Government Charges on Disposal of Construction and Demolition Waste: A Hong Kong Case Study

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Abstract: With the purpose of reducing the amount of construction and demolition (C&D) waste disposed to landfills, many countries and municipalities have introduced increasingly stringent C&D waste disposal charges (CDWDC) but the level of CDWDC is often determined without a clear understanding of its broad and complex impacts. Against this background, this paper aims to propose a system dynamics (SD) model that can help predict CDWDC's environmental implications as well as its financial implications. Specifically, the proposed model explains complex causal relationships between variables such as the level of CDWDC, the amount of C&D waste disposed to landfills, the government's revenues from CDWDC as well as the costs of supplying and operating landfills over time. For a case study, the developed model is customized and calibrated with actual data from Hong Kong, where the remaining capacities of existing landfills are limited and the need for supplying more landfills is imminent. The simulation analysis with the model predicts that the current charging levels may not be high enough to effectively control the amount of C&D waste disposed to landfills or to compensate for the costs to the government of supplying additional landfills. The analysis also predicts how much illegal dumping may increase as the level of CDWDC increases. This case study illustrates that the proposed SD model can help policy makers to see the potential impacts of increased CDWDC on the amount of C&D waste disposed to landfills, government costs and the amount of illegal dumping of C&D waste; and can therefore help them to determine the most appropriate level of CDWDC.

Keywords: construction and demolition (C&D) waste; C&D waste disposal charges; supply of landfills; system dynamics

1. Introduction and Research Backgrounds

As the population grows globally and human habitats are increasingly urbanized, how to handle the vast amounts of solid waste generated from human activities in urban areas has become a critical issue for sustainable development in many countries and municipalities. In particular, how to handle the waste generated from construction and/or demolition processes, that is, construction and demolition waste (C&D waste), has become a matter of great concern in many regions around the world because of the significance of the amount of C&D waste disposed to landfills. For example, in China, the amount of C&D waste is more than 1.5 billion tons per year, only approximately 5% of which is recycled and reused [1]. In Australia, a total of 19 million tons of C&D waste were generated from 2008 to 2009, and among them, 8.5 million tons were disposed to landfills [2]. In Hong Kong, on average 3942 tons of C&D waste were received at landfills per day during 2014, accounting for 27% of the total solid waste disposed to landfills in Hong Kong [3]. Despite the government's efforts to encourage the reuse and recycling of C&D waste, the amount of C&D waste disposed to landfills increased by 9.8% from the previous year in Hong Kong in 2014 [3]. In Tehran, the capital city of Iran, only 26% of C&D waste was recycled during the period from 2011 to 2017 [4]. In Europe, since the European Union adopted the Waste Framework Directive (WFD) in 2008 that sets a target for recovery rate of C&D waste, there has been improvement in the recovery rate of C&D waste across European countries. For example, in the United Kingdom the recovery rate of C&D waste has been significantly improved, from 69% in 2005 [5] to near 90% in 2017, which is above the target (70%) set by WFD [6]. In Norway, the total amount of C&D waste was 814,000 tons in 2013 and among them 603,000 tons of waste (74%) were recovered and 210,000 tons of waste (26%) were disposed [7]. However, the average C&D waste recovery rate of 27 EU countries of 46% [8] shows that still a large portion of C&D waste is disposed to landfills in many European countries as well. With this being the case, attention to how to reduce C&D waste disposed to landfills has increased during the last decade around the world and especially in densely-populated regions like Hong Kong, China and Europe [9–12].

With the purpose of reducing the amount of C&D waste disposed to landfills, policy-makers in local or central governments have introduced increasingly stringent regulations and fees on the disposal of C&D waste, namely C&D waste disposal charges (CDWDC) and such government-initiated programs has been found to be generally effective in controlling the amount of C&D waste [13–15]. Imposing CDWDC can make C&D waste producers responsible for the waste they generate, as often referred to as the "polluter pays principle", and ultimately demotivate disposal of C&D waste to landfills. Additionally, from a government's perspective, CDWDC function as a practical means of getting compensated for the government's costs for waste handling including the supply and operation of landfill sites. However, some literature also reports mixed results on the effectiveness of CDWDC and especially in continuously curtailing the amount of C&D waste disposed to landfills over the long term and indicates that CDWDC have limitations in changing waste producers' behavior or work methods [5].

As an effort for addressing the problem of increasing amounts of C&D waste and depletion of landfill space worldwide, researchers have developed various approaches for understanding the lifecycle of C&D waste and for quantifying, tracking and predicting the amounts of C&D waste generated, reused, recycled, and/or landfilled at various levels. Examples of such approaches are project- or industry-level waste quantity estimate (e.g., [16–19]), BIM-based building-level waste quantity estimate (e.g., [20]), industrial ecology modelling (e.g., [21]) and project- or regional-level SD modelling (e.g., [9,22,23]).

Among these approaches, SD modelling has frequently been used for investigating the complex system behavior of the variables that are involved with the lifecycle of C&D waste and for finding ways to reduce the amount of C&D waste ending up in landfills. As an example, Zhao et al. [23] used the SD approach to model causal relationships among the amounts of C&D waste generated and reused or recycled for multiple types of construction materials (e.g., concrete, wood, brick, steel) and their influencing factors (e.g., disposal costs, landfilling costs, recycling costs, transportation costs and the ratio of these costs to each other), for a Chinese city, Chongqing. In another study, Hao and her colleagues [9,10] designed quantified models to predict the amount of C&D waste generated and disposed to landfills as well as the remaining or additionally needed amounts of landfill space in the regions in the future according to a few scenarios. Yuan and Wang [22] also used the SD approach for studying the impact of different levels of the waste disposal charges on the amounts of C&D waste generated, recycled, landfilled and even illegally disposed of, using simulations with the model. In particular, they explicitly modelled the causal links between waste disposal charges and waste producers' reactions to them, including both compliance (e.g., recycling) and non-compliance (e.g., illegal dumping) behaviors. Most recently, Jia et al. [1] used SD modelling and simulation approach to predict the impact of penalties and subsidies to control the amount of C&D waste.

These previous works made significant advances in the holistic approach to C&D waste management using SD modelling and simulation, incorporating C&D waste generation [9,11], impacts of CDWDC [9,11,23], consumption of landfill space [9] and waste producers' reactions to CDWDC [22]. However, these previous SD models have limitations in representing the financial aspect of a government's C&D waste management, such as revenues from CDWDC and the government's costs for supplying and operating landfills.

Against this background, this paper's aim is to propose a system dynamics based approach to CDWDC integrating their environmental implications (e.g., reduction of C&D waste disposed to landfills caused by CDWDC) with financial implications (e.g., the government's cost recovery by revenues from CDWDC). Specifically, this paper proposes a system dynamics (SD) model that considers complex causal relationships among the variables that would affect the effectiveness of CDWDC from the governments' perspective, such as the amount of C&D waste disposed to landfills, the amount of currently available or additionally needed landfill space, the government's revenues from CDWDC and their costs of supplying and operating landfills over time. It is expected that the proposed SD model will allow policy-makers to consider various implications of different levels of CDWDC in a holistic manner and help them to make an informed decision about the most appropriate level of CDWDC. To demonstrate the usefulness of the proposed SD modelling approach, this paper uses a case example in which the SD model is customized and calibrated with actual data from Hong Kong, where remaining capacities of existing landfills are limited and the need for supplying more landfills is imminent [5,15].

2. Research Methodology

This research was conducted in the following six sequential but iterative steps as outlined by Sterman [24] (Figure 1).

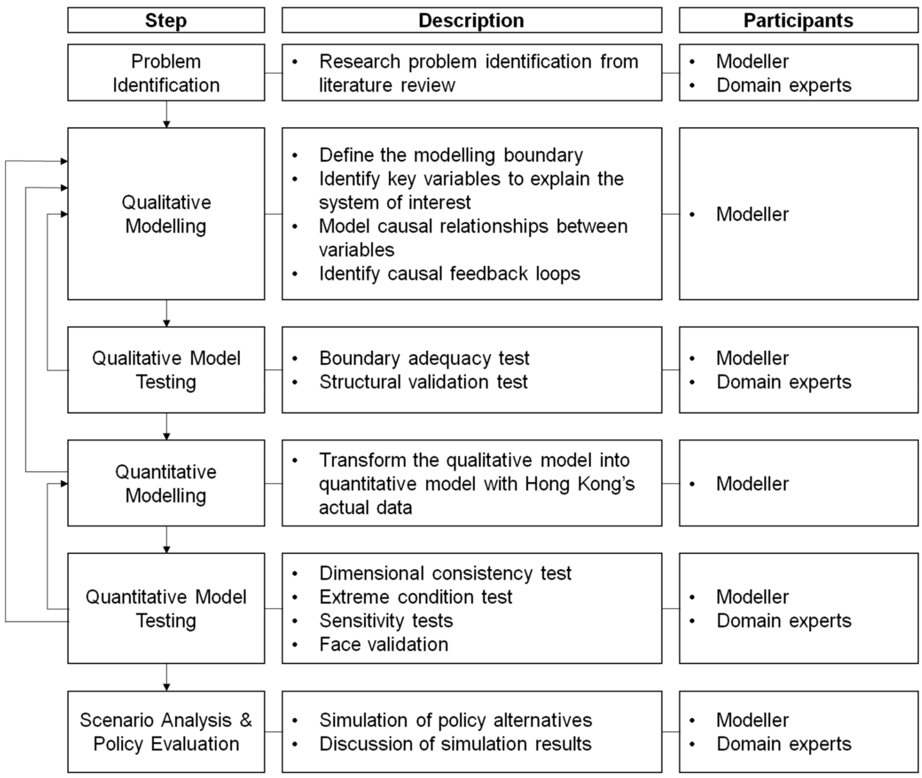

Figure 1. Research methodology.

Step 1: At the beginning of this research, the problem (i.e., depletion of landfills and increasing amount of C&D waste disposed to landfills) and the modelling goal (i.e., finding an appropriate level of CDWDC to address the problems) were identified. **Step 2:** A qualitative SD model, often referred to as a causal diagram or an influence diagram [25], was developed by identifying a set of variables involved with the phenomena being addressed and causal relationships between the variables were identified based on the literature. As a result of this causal modelling, several feedback loops involved with the phenomena were identified. **Step 3**: The validity of the qualitative model was examined using the boundary adequacy test and the structural validation test. The boundary adequacy test examined whether the model includes all the essential variables required to explain the behavior of the system and addresses the problems identified at the first step, while the structural validity test examined the exploratory power of the model in relation to the observed or reported behavior of the real system [24–26]. **Step 4:** The qualitative model was transformed into a quantitative model by assigning a computational model (e.g., an equation, a lookup function) for each causal relationship and populating the model with parameters that represent a state of the real system being investigated. At this step, the quantitative model was customized and calibrated to the data representing Hong Kong's current situation and government's policies regarding C&D waste management for the case study. **Step 5:** The quantitative model was verified and validated using several test methods, including the dimensional consistency test, the extreme condition test, the sensitivity test and the face validity test, as recommended by authoritative SD researchers [24,26]. **Step 6:** The quantitative model was used for simulating different scenarios to see the impacts of policy alternatives, that is, various levels of CDWDC in this case. The simulation results are then used to infer how well each policy alternative will meet the evaluation criteria in the real world. The Vensim PLE software (www.vensim.com), which has been used in many other system dynamics studies in waste management [22,23], was used as the computer modelling and simulation environment throughout the modelling and simulation processes in this research.

Clients' involvement is often recommended in an SD modelling work because the knowledge needed for constructing a causal model often exists only in the form of a mental model in the clients' heads and once a model is completed, only they can judge its usefulness for validation purposes [24,27]. Another reason for involving clients in SD modelling is that the insights generated from the simulation are implemented in the real world only when the clients can make sense of all the assumptions and justifications used in the model and have confidence about the working of the model [28]. Therefore, two domain experts who have extensive experience in C&D waste management as well as modelling were involved throughout the SD modelling and simulation processes in this research, acting as "the clients." In the modelling process, the experts communicated with the modelers regularly, providing their knowledge and insights into qualitative/quantitative relationships between variables as well as their estimates on parameter values. They also participated in the model review process at the end of step (2), (4) and (6), for validation purposes.

3. System Dynamics Modelling: Based on Hong Kong's Case

In this paper, Hong Kong's case is used in the modelling and simulation process for demonstration purposes. The following sections describe the background of the case and the development of the qualitative and the quantitative SD models and the efforts for validating the models, in sequence.

3.1. Background of the Case

Currently, Hong Kong has the following three landfill sites receiving different types of solid waste including C&D waste: South East New Territories (SENT) Landfill, North East New Territories (NENT) Landfill and West New Territories (WENT) Landfill. For the last few decades, Hong Kong has struggled with a rapidly increasing amount of C&D waste and their disposal to landfills and in response to the problem, the government has introduced a number of measures and regulations to control the amount of C&D waste [5]. In particular, in 2006 the Hong Kong government introduced CDWDC for encouraging the reduction, sorting, reuse and recycling of C&D waste and for slowing down the depletion of existing landfills [5,15]. Under the current scheme, contractors are charged HK$125 (approx. 16 USD) per ton of non-inert C&D waste disposed of at landfills; HK$100 (approx. 13 USD) per ton if the waste (a mixture of inert and non-inert waste) are admitted by off-site sorting facilities; HK$27 (approx. 3.5 USD) per ton if the waste consist entirely of inert materials that can be disposed to the public fill reception facilities [29].

The Hong Kong government predicted that the existing landfill sites would be consumed within ten years [30,31]. Under this circumstance, the Hong Kong Green Building Council and the Business Environment Council formed a joint working group to hear from different stakeholders and propose new charging levels for CDWDC based on their consensus [32]. As a result, new charging levels were proposed for different types of facilities receiving C&D waste, as follows: HK$71 (approx. 9 USD) for public fill reception facilities, HK$175 (approx. 22 USD) for sorting facilities and HK$200 (approx. 25 USD) for landfills. Currently, this proposal waits for public consultation, which will come into effect from April 2017.

Understandably, different stakeholders have different opinions regarding the proposed charging levels. For instance, pro-environmental groups argue that the proposed charging levels are not stringent enough to achieve the goal of minimizing C&D waste, while construction and demolition contractors argue that the proposed charging levels are infeasible to them. Meanwhile, a debate has emerged regarding which method should be used for determining the charging levels in the review of the new charging scheme. However, a solid foundation on which stakeholders can engage in the decision process for determining the charging levels is still lacking [33].

3.2. Qualitative Modelling

Under the circumstance, three groups of questions would warrant an answer for finding a suitable level of CDWDC: (1) Questions regarding the environmental implications of CDWDC: How large will the impact of different levels of CDWDC be on the amount of C&D waste generated or disposed to landfills? Will there be any adverse side effects of increased levels of CDWDC? (2) Questions regarding the existing and additionally required landfill space: How quickly will the existing landfill space be consumed? When will the government need to supply additional landfill sites accordingly? (3) Questions regarding the government's costs and financial implications of CDWDC: What will the government's costs of supplying and operating landfill sites be? How much will the government's revenues from CDWDC help the government to recover the costs over time?

To address these questions by SD modelling and simulation, the main variables that need to be included in the model are identified and also categorized into three groups: (1) variables related to the environmental implications of CDWDC such as motivation of minimizing waste generation, motivation of increasing on-site sorting, motivation of increasing off-site sorting, motivation of illegal dumping, the amount of C&D waste generated, the percentage of C&D waste disposed to landfills and the amount of C&D waste disposed to landfills. (2) variables related to the existing and prospective landfill space, such as the rate of consumption of landfill capacity and the need of supplying additional landfills and (3) variables related to the government's costs and financial implications of CDWDC, such as government's revenues from CDWDC, government's costs for supplying and operating landfills and ratio of governmental costs to the revenues from CDWDC.

Qualitative causal relationships among these variables can be modelled into a causal diagram, as shown in Figure 2, based on the findings from the literature and the knowledge acquired from the experts participating in this research.

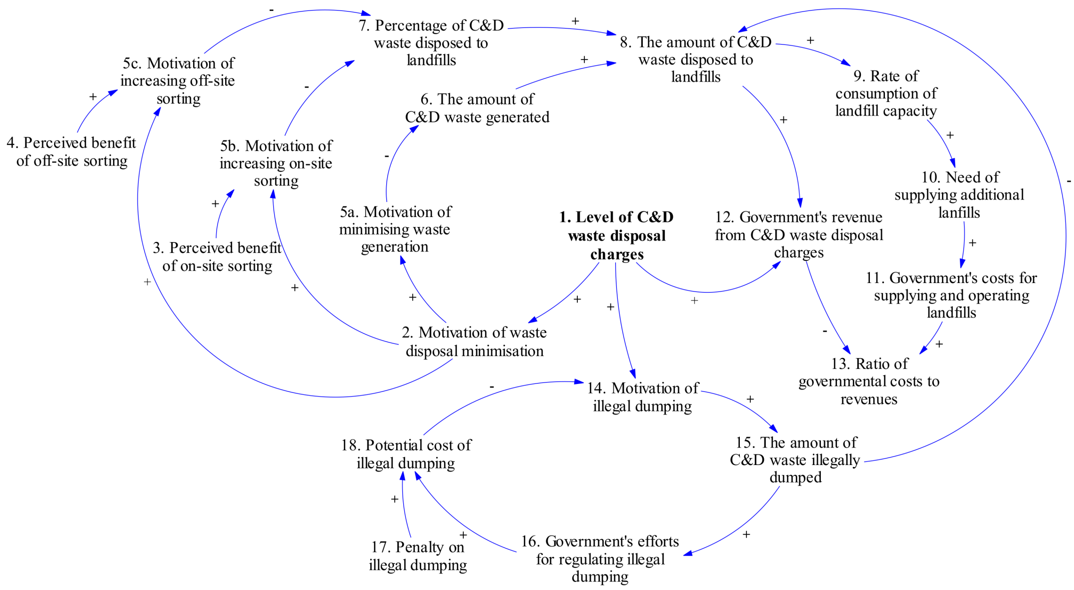

Figure 2. Causal diagram of C&D waste generation and disposal in Hong Kong.

This causal diagram captures several important causal chains, through which an increase of CDWDC can impact other variables in the model. Figure 3 shows that a high level of CDWDC can cause a decrease in the government's costs for supplying and operating landfills over time. This causal chain is supported by a number of theoretical work (e.g., the theory of planned behavior [34] and empirical results (e.g., [22,35]). On the other hand, Figure 4 shows that it is not as certain whether a high level of CDWDC will lead to an increase or a decrease in the government's revenues from CDWDC. This is due to the dual effect of CDWDC as a source of revenue that occurs only when C&D waste is disposed of and as a demotivator of that exact happening at the same time. Due to this uncertainty, when the two causal chains (i.e., chains depicted in Figures 3 and 4) are combined, it is even more difficult to predict the dynamic patterns of government's revenues and costs regarding C&D waste management under the different scenarios regarding CDWDC.

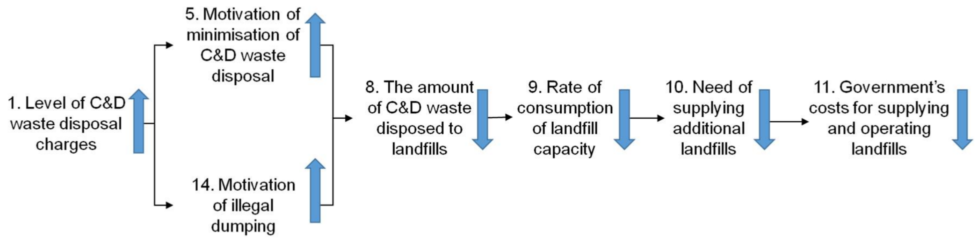

Figure 3. Impact of a high level of CDWDC on government's costs for supplying and operating landfills.

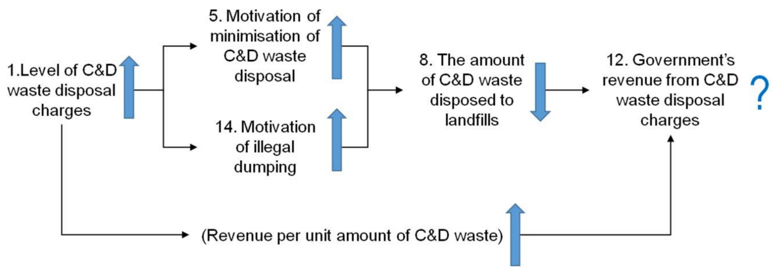

Figure 4. Impact of a high level of CDWDC on government's revenues from CDWDC.

3.3. Quantitative Modelling

As a next step, the qualitative SD model is transformed into a quantitative, stock-and-flow-based model with all the auxiliary variables added and with the mathematical relationships between variables and model inputs (i.e., parameter values) entered into the model (Figure 5). Specifically, the stock-and-flow diagram is informed by the real data representing Hong Kong's current situations and the government's existing plans and policies, such as annual increase rate of C&D waste, annual increase rates of the amount of C&D waste annually disposed of and accumulated in existing landfill sites, currently remaining capacities of existing landfill sites (i.e., SENT, NENT, WENT), the government's current plan to spend for constructing new landfill sites, the current and proposed levels of CDWDC and the amount of C&D waste estimated to be illegally disposed of Table 1 shows a summary of how the main variables were quantified in the model. More details of each of the mathematical models and parameter values can be found in the Supplemental Data of this paper.

Table 1. Summary of the main variables quantified in the model.

No.	Variables (unit)	Format	Sources
1	Annual increase rate of C&D waste (percentage)	A lookup function showing the annual C&D waste increase rate for each year	[22,36,37]
2	Motivation of waste management (dimensionless)	A lookup function showing the levels of motivation of waste management according to the different levels of CDWDC	[22,33]
3	Motivation of waste minimization (dimensionless), Motivation of waste recycling (dimensionless), Motivation of on-site sorting (dimensionless) and Motivation of off-site sorting (dimensionless)	A ratio to the general Motivation of waste management	Knowledge from experts participating in research
4	Annual amount of C&D waste generated(ton/year)	An integral function of annual increase rate of C&D waste	[38]
5	Decreasing rate of landfilling (percentage)	A lookup function showing the impact of motivations of recycling, waste minimization, off-site sorting and on-site sorting on the rate of landfilling	[22,33,34,38]
6	Rate of illegal dumping (percentage)	A lookup function showing the impact of different levels of CDWDC on the rate of illegal dumping in Hong Kong	[39]
7	Expected cost of violation of regulation (HK Dollars)	The level of penalty on illegal dumping × the probability of receiving penalty	[22,40]
8	Remaining capacity of existing landfill sites (ton)	An algebraic function of the current remaining capacity of landfill sites in Hong Kong and Accumulated amount of C&D waste landfilled	[41]
9	Extensions of SENT, NENT and WENT (HK Dollars)	A quasi step function representing the Hong Kong government's current plan to spend financial resources to extend the existing landfill sites and supply more landfill space	[42–44]

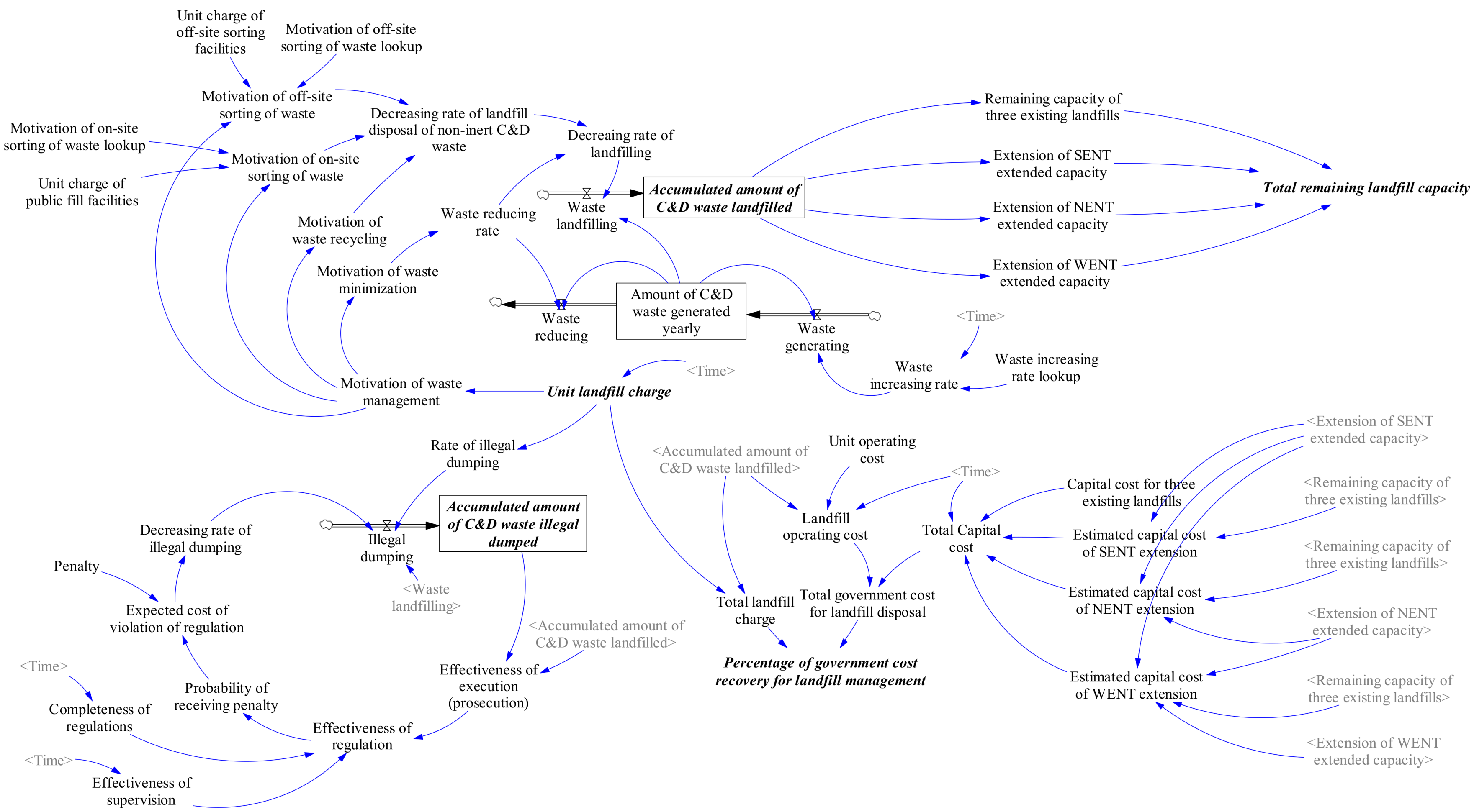

Figure 5. Final stock-and-flow diagram.

In addition, the following assumptions are made based on the literature and public data as well as in consultation with the experts participating in this research and used in the quantitative SD model:

- The increasing rate of C&D waste generation would be equal to the increasing rate of the amount of construction work.
- The motivation for on-site sorting, off-site sorting and recycling would contribute to the decreasing rate of inert waste landfilled equally.
- The ratio of C&D waste landfilled to the total amount of solid waste landfilled would be steady at the current ratio, approximately 25%.
- The ratio of inert waste to the total C&D waste landfilled would stay at the current ratio, approximately 10%.
- The extension of existing landfills will take place in the order of SENT, NENT and WENT, as they are consumed.

3.4. Model Validation

The validation tests used in this study include: (1) boundary-adequacy test: the variables in the causal loop diagram and the stock-flow diagram were examined to see whether the variables are relevant to the research questions and objectives and whether the qualitative model is transformed into the quantitative model correctly; (2) structure verification test: the causal paths and loops identified in the models were examined to see their explanatory power for the situation under investigation; (3) dimension consistency test: the "units check" function in the Vensim software was used to check whether the model is dimensionally consistent; (4) parameter verification test: the parameter values used in the quantitative model were examined to make sure that they are from reliable sources of information and with plausible justifications; and (5) extreme conditions test: the model was tested under the lower and upper extreme conditions for main independent variables (e.g., very high and low charging levels for CDWDC) to see if the model's behavior is plausible even under such extreme conditions. After several rounds of modelling iterations, the results of all these tests demonstrated that the model meets the requirements based on the modelling objectives and therefore, helped gain confidence with using the model in the following simulation experiments and scenario analysis.

As described previously, the two domain experts were involved with the model review and validation processes in this research. Their assessment focused mainly on the explanatory power of the model and the plausibility of the SD simulation results. During the modelling iterations, the experts' comments were used to confirm the model's ability to reproduce the patterns observed by them in real worlds. In addition, the simulation results from the base model, which is designed to represent Hong Kong's current situation, were compared with the real data collected from EPD (from the year 2010 to 2014) to check the model's quantitative performance.

4. Simulation Results and Discussion

At the completion of simulation modelling, two phases of simulation experiments were designed. The first phase involves running the base model, which aims to predict the consequences if there is no change in the levels of CDWDC. The second phase involves conducting a what-if scenario analysis for different levels of CDWDC. In both simulation experiments, the simulated period of time was set to 25 years, from 2006 to 2030.

4.1. Base Model Simulation Result

For the base run simulation, real data for *Unit landfill charge* and *Penalty on illegal dumping* representing Hong Kong's current situation (HK$125/ton and HK$10,383.2, respectively) were used as parameter values in the model. The simulation result shows an increasing pattern of the accumulated amount of C&D waste disposed to landfills as well as the decreasing pattern of available landfill capacities over the years. As mentioned in the methodology section, the simulation data for the year 2010 to 2016 were compared to the real data and this comparison showed that the simulation data have less than 10% difference from the real data for the two variables over the period of time.

Expectedly, the model predicts that the accumulated amount of C&D waste landfilled will increase continuously from 2016 to 2030 with a slightly increasing rate of increase (i.e., an exponential curve) due to the increasing development of new built environments and demolition of old buildings in Hong Kong. This result also implies that the current levels of CDWDC would not be effective for suppressing the amount of C&D waste generated and disposed to landfills every year.

The graphs in Figure 6 also show that the overall landfill capacities will continuously decrease as the accumulated amount of C&D waste increases until the government provides additional landfill space. According to the Hong Kong's current plan [42–44], extension projects for existing landfill sites are modelled to take place in sequence in order of SENT, NENT and WENT. Therefore, when a landfill extension project begins, there will be a sharp increase in the landfill capacity as shown in the graph. More specifically, it is predicted that the extension of SENT, NENT and WENT will take place before 2020, 2026 and 2029, respectively, in the current scenario.

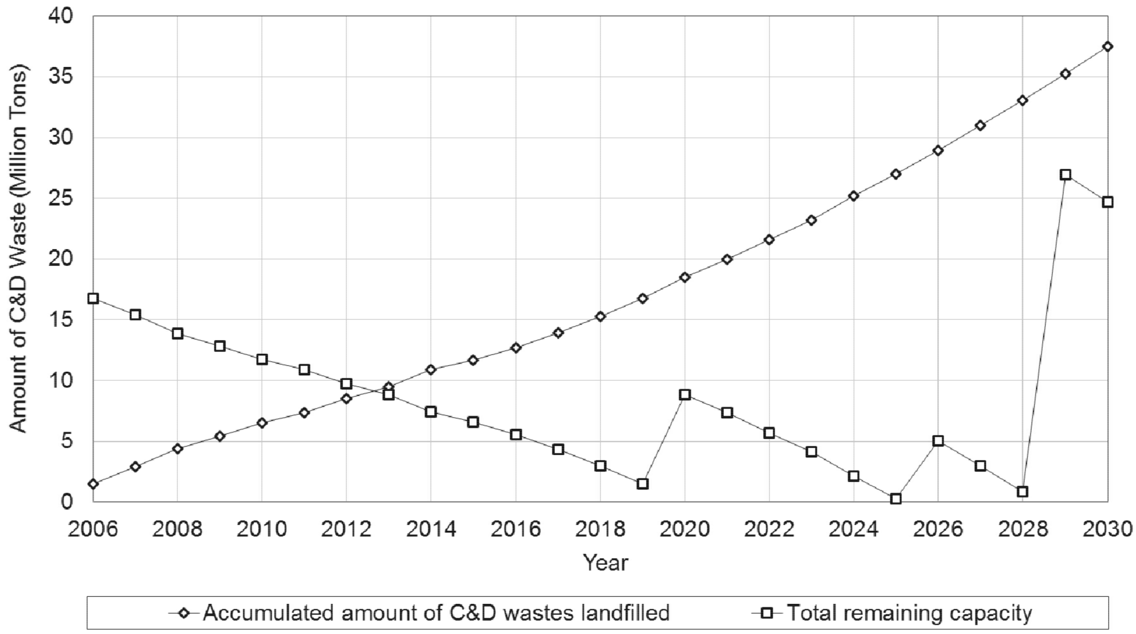

Figure 6. Base run simulation—total remaining landfill capacity and accumulated C&D waste landfilled.

In addition, the model predicts that the accumulated amount of C&D waste illegally dumped will also keep increasing, as shown in Figure 7. The fact that the pattern of increase of the accumulated amount of C&D waste illegally dumped is similar with that of the accumulated amount of C&D waste landfilled implies that there would not be a significant difference in the rate of illegal dumping out of the total amount of C&D waste disposed to landfills if the current level of CDWDC is used continuously, which supports Yu et al.'s [5] finding about CDWDC.

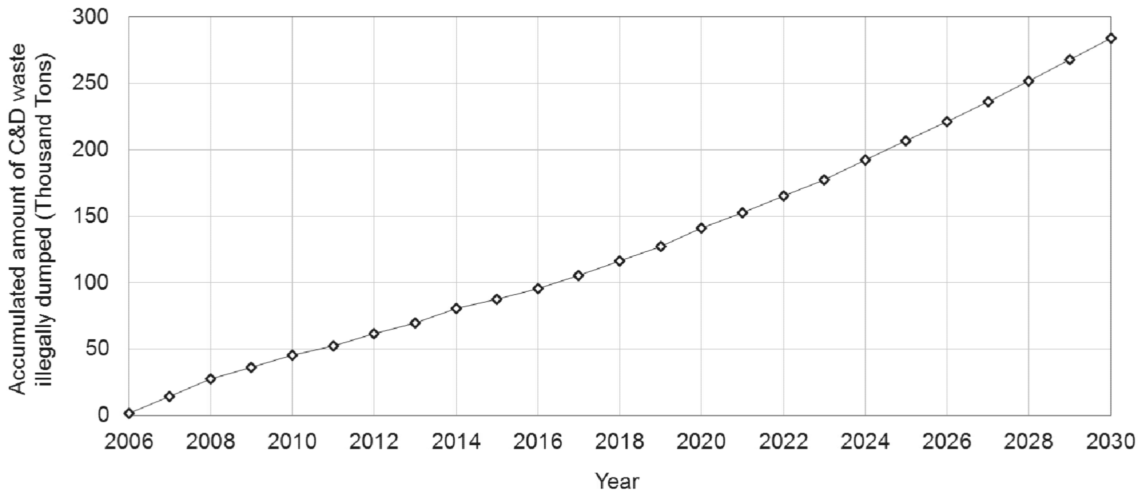

Figure 7. Base simulation—accumulated amount of C&D waste illegally dumped.

Figure 8 shows how large percentage of government's cost would be recovered by the revenues from CDWDC over the period of time if the current levels of CDWDC are used continuously. The percentage of government cost recovery would be affected by both the government's costs for supplying and operating landfill sites and the revenues from CDWDC. The simulation result shows that the percentage of government's cost recovery from CDWDC would be approximately 20–30% from 2016 onward if the current levels of CDWDC are used continuously. The drop in the percentage of government's cost recovery around 2016 reflects the Hong Kong government's new target to fully recover its C&D waste management costs from the charges on the disposal of waste under a stricter "polluter-pay-principle" [40].

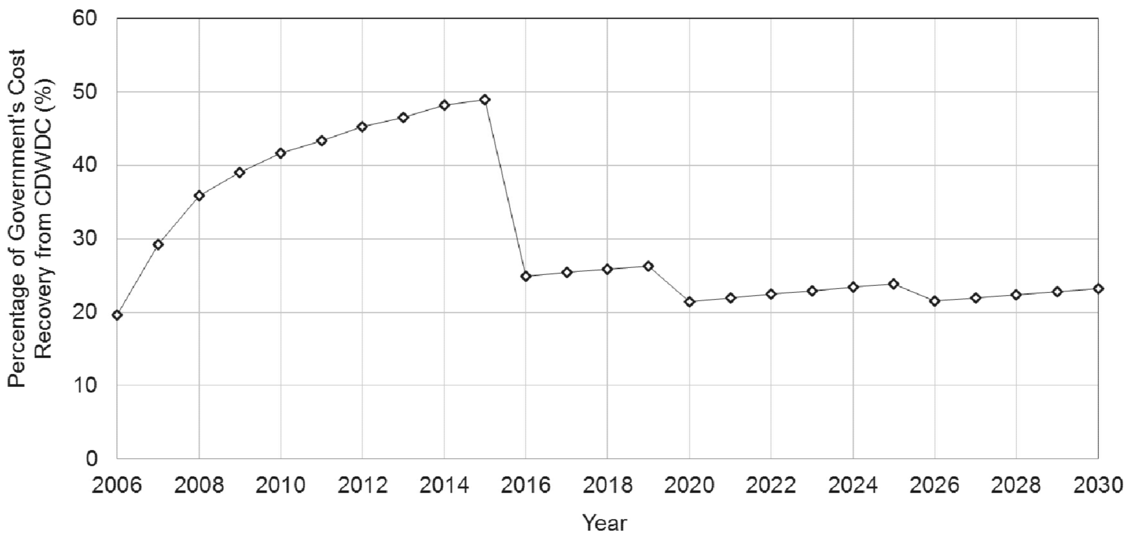

Figure 8. Base run simulation—percentage of government cost recovery.

4.2. Scenario Analysis

The simulation result from the base model clearly showed that the current levels of CDWDC would not be effective for suppressing the increasing pattern of the amount of C&D waste disposed to landfills or for improving the government's cost recovery rate. Therefore, the result implies that a more significant increase of CDWDC would be necessary to meet the government's goal of reducing the amount of C&D waste disposed to landfills and increasing the government's cost recovery from CDWDC. The second phase of simulation experiments, therefore, aims to predict the financial and environmental impacts of different levels of CDWDC. In this what-if analysis, the simulation model took seven different input values for *Unit landfill charge*, incrementally changing from HK$125/ton up to HK$425/ton and the behavior of the model was observed for each scenario.

The graphs in Figure 8 show the impact of different levels of CDWDC on the accumulated amount of C&D waste landfilled. The model predicts that there would be a significant divergence on the accumulated amount of C&D waste in landfills depending on the level of CDWDC. Specifically, it is predicted that in 2030 the accumulated amount of C&D waste disposed to landfills would be around 25 million tons if the unit landfill charge level is increased to HK$425. This means that there would be nearly 50% reduction in the accumulated amount of C&D waste in landfills by 2030 if the level of CDWDC can increase from HK$125 to HK$425.

However, the graphs in Figure 9 also show that there is not much further reduction in the accumulated amount of C&D waste landfilled after the unit landfill charge increases to HK$325, while there is a somewhat significant gap in the model behavior between when the unit landfill charge is HK$275 and when it is HK$325. This implies that there might be a "tipping point" between these levels of CDWDC in terms of the resulting reduction in the amount of C&D waste landfilled.

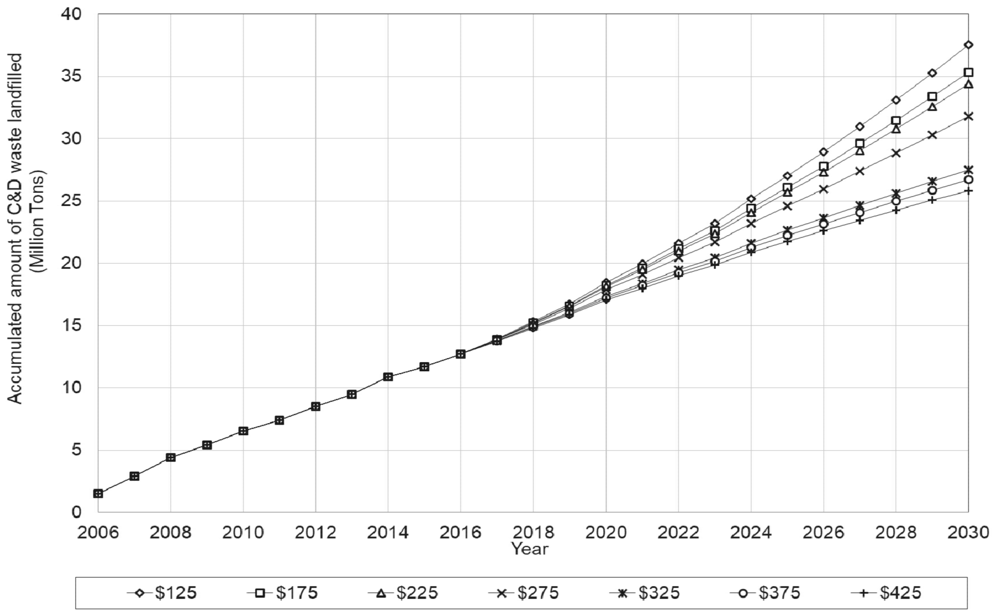

Figure 9. Scenario analysis –amount of C&D waste landfilled by unit landfill charge.

Additionally, the model predicts that the rate of illegal dumping will vary substantially as the charging levels increase (Figure 10). Specifically, in 2030 the accumulated amount of C&D waste illegally dumped is predicted to be under 300 thousand tons in total with the current level of CDWDC, while it will be over 650 thousand tons if the charging level is increased to HK$425. This result simply shows that waste generators would be much more willing to take risks to dump the C&D waste illegally to reduce their costs. Therefore, this result implies that an effective detection and penalization of illegal dumping (c.f. [1]) should be entailed for a high level of CDWDC to be effectively implemented.

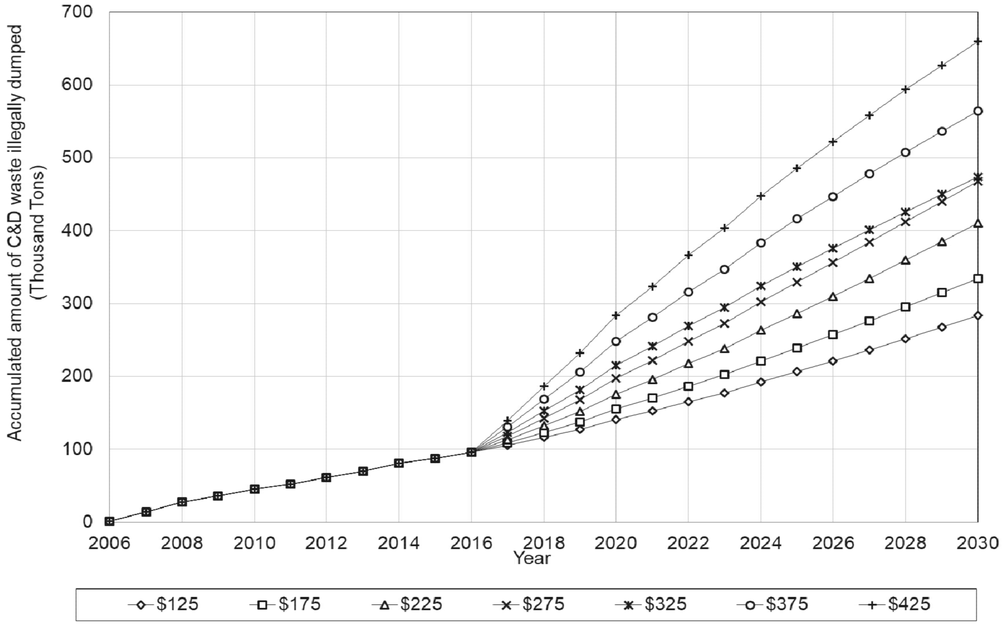

Figure 10. Scenario analysis—amount of C&D waste illegal dumped by unit landfill charge.

Figure 11 shows a comparison across different CDWDC scenarios in terms of the government's cost recovery. The cost recovery is affected by the amount of waste landfilled as well as by the charging level. The model predicts that the government's cost recovery rate would be substantially improved as the charging level increases. The model predicts that the government would be able to recover 75–90% of the entire costs of supplying and operating landfills if the charging level can be as high as HK$425. The nearly equal intervals between government's cost recovery rates at different levels of CDWDC observed in the graph are due to the fact that the variation in the yearly amount of C&D waste disposed to landfills depending on the level of CDWDC is not large (i.e., 5–10% difference of the total amount of C&D waste landfilled per year) but the variation in the charging levels are much more substantial (i.e., 240% different between HK$125 and HK$425).

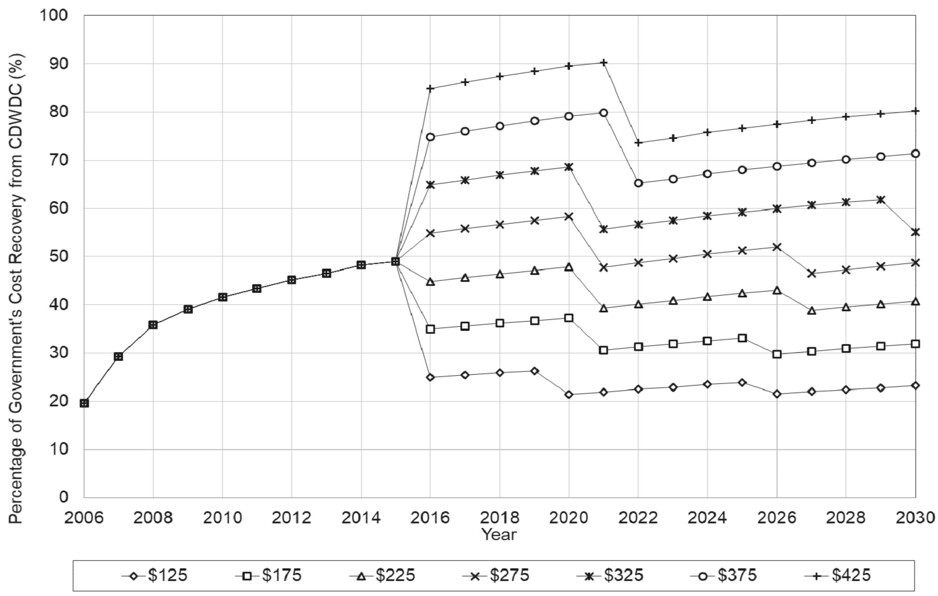

Figure 11. Scenario analysis—percentage of government cost recovery by unit landfill charge.

One can interpret these simulation results and find that the level of CDWDC would be only one of several critical factors that influence the amount of C&D waste disposed to landfills. There would be still a meaningful decrease (5–10%) in the amount of C&D waste disposed to landfills each year if the level of CDWDC increases but the contractors' financial burdens associated with CDWDC would increase much more dramatically. If the level of CDWDC increases dramatically, it will help the government financially but the government would also need to think about how to effectively prevent illegal dumping, which is expected to increase also significantly as the level of CDWDC increases. If such enforcement efforts are not effectively entailed, illegal dumping can pose a major threat to the natural environment of Hong Kong, as shown in the simulation result presented above as well as in previous works such as Yuan et al. [35] and Yuan and Wang [22].

As a summary, the scenario analysis results show that the current charging level (HK$125/ton, equivalent to 16 USD/ton) would not be effective for slowing down the depletion of landfill capacity or for improving the government's cost recovery in Hong Kong. The simulation results also suggest that a higher charging level (e.g., HK$325, equivalent to 41 USD/ton) can be more effective for achieving those goals, reduction in the amount of C&D waste disposed to landfills and improvement in the government's cost recovery. This suggests that charging levels that are even higher than the ones the government has proposed (e.g., HK$ 200 for C&D waste disposed to landfills, [45]) would be necessary to effectively control the amount of C&D disposed to landfills. This argument is in line with the recent finding that government regulations and supervision would be the strongest motivator for contractors to adopt C&D waste minimization strategies [13]. However, before the adoption of higher levels of CDWDC, the government will need find a way to address the potential issue of increased illegal dumping as it is clearly the case according to the simulation result.

5. Conclusions

The SD modelling approach explained in this paper addresses how to model the complex phenomena regarding the disposal of C&D waste to landfills and how to determine an appropriate level of CDWDC that can help the government control the amount of C&D waste disposed to landfills with its environmental implications as well as financial implications considered. In this research, first a qualitative causal model was developed and subsequently a quantitative model was developed using the data representing Hong Kong's situation. Over the course of development, the model has been verified and validated through a series of tests involving domain experts and the final model showed its capability to produce predictions for important variables to be considered when deciding the most appropriate level of CDWDC, such as the amount of C&D waste disposed to landfills, the government's cost recovery from CDWDC and the expected amount of illegal dumping.

The proposed SD modelling approach helps advance the SD modelling-based approach to C&D waste management by introducing financial variables and integrating them with the environmental impact variables (e.g., remaining landfill capacities) within the model. It is believed that the financial aspects added into the model can help make the model more useful in assisting government policy makers. It is believed that, consequently, the proposed SD model with a more comprehensive set of variables would allow examining the broader impacts and implications of different levels of CDWDC and enable the policy makers to determine the most appropriate level of CDWDC from a more holistic perspective.

However, future research would be required to achieve the full potential of the proposed SD-based approach. First, the proposed SD model needs to be further developed by incorporating differentiated construction and demolition charges and the reliability of the model needs to be tested with the more diversified and dynamic charging scheme. For example, the current SD model does not consider variations in landfill site operation costs over time. Similarly, the current model does not consider the possibility of variations in the level of penalties on illegal dumping (c.f. [1]). Since these variables can be impactful on the behavior of the model, more diverse scenario analysis and sensitivity analysis would be required to achieve the full potential of the proposed approach. Second, there are several components in the model which can be further detailed for enhancing the model's explanatory power. For example, the details of the charges at different kinds of facilities receiving C&D waste (e.g., off-site sorting facilities and public fill reception facilities) can be included in the model, which will allow more fine-tuned scenario analysis for the impact of the different levels of government's CDWDC. Another area of research would be fine-tuning the assumption regarding the relationship between the accumulated amount of C&D waste and the total solid waste disposed to landfills. A constant ratio between the amounts is used in the current model but differentiating a number of different kinds of solid waste and associating them with different charging levels would allow more fine-grained predictions and more insights into more fine-tuned policy alternatives. Third, more refinement of modelling elements and assumptions and more tests for validation purposes will help increase the model's credibility even further. Currently, the usefulness of the model has been tested only against Hong Kong's case and therefore more studies using the similar SD modelling approach will improve the confidence of using the SD model and also will help demonstrate the generality and reliability of the model in other cases (e.g., external validity).

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