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Construction and demolition waste disposal charging scheme design

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Abstract

Construction and demolition waste disposal charging is a critical component in construction waste (CW) management. Over the past few decades of implementation around the world, the effectiveness of waste disposal charging in decreasing negative environmental impact is gradually being questioned. This paper identifies two intertwined issues that have not attracted sufficient attention in actual practice. One is the consideration of contractors' behavior, which is economically driven. Another is the influence of waste transportation, which is also a major stream of environmental pollution. These two aspects significantly affect the effectiveness of the waste disposal charging scheme. Contractors may not transport their generated CW to appropriate disposal facilities. They make decisions based on the disposal and transportation cost. To address this problem, this paper proposes a general construction and demolition waste disposal charging design methodology in which contractors' behavior and the influence of waste transportation are taken into account. A mixed-integer programming model is developed for the optimal design of the charging fees, which analytically formulates both of the abovementioned aspects. Furthermore, we developed a model that partially modifies the current charging scheme to better fulfill the environmental protection objective. Extensive numerical experiments demonstrate that the proposed methodology can effectively change contractors' waste disposal decisions and significantly decrease the negative environmental impact of construction and demolition waste. This study contributes to a new perspective to better design the construction and demolition waste disposal charging scheme and has a wide range of applicability.

1 | INTRODUCTION

Construction and demolition waste, called construction waste (CW) here for brevity, is the waste arising from construction, demolition, and renovation projects. CW is the largest source of solid waste globally (Gálvez-Martos et al., 2018; Lu et al., 2016; Maués et al., 2021). For instance, the European construction sector generates 0.82 billion tons of CW each year, which accounts for 46% percentage of the total waste produced according to Eurostat (Gálvez-Martos et al., 2018). Although the environmental pollution associated with CW is not intensive compared with other waste streams, total pollution from CW is considerable due to its high volume and weight. Therefore, the management of CW is an important aspect of environmental protection programs (Rafiei & Adeli, 2016; Zavadskas et al., 2018). For instance, the Hong Kong Environmental Protection Department (EPD) and its executive arms have introduced dozens of CW management strategies including regulations and initiatives over the past few decades (Chen & Lu, 2017; Lu & Tam, 2013), and the European Union established a dedicated working group to make recommendations for the management of CW, which was reported to work well (Duan et al., 2015). In 2018, the European Commission introduced a new protocol to further promote and elaborate the management of CW (European Commission, 2018; Zhang et al., 2022).

Economic incentives or equivalent punishment are effective tools to motivate contractors to change their CW disposal behavior, and they have been implemented in many areas around the world (Ding et al., 2022; Hao et al., 2019; Lv et al., 2021; Wu et al., 2017). For example, Andersen (1998) claimed that a CW tax reduced the amount of CW in Denmark by approximately 64% in 6 years. Similar effects have been observed in the Netherlands, where the amount of landfill waste decreased by approximately 6 kilotons during the 8 years after implementing a landfill tax (Bartelings et al., 2005). Countries in East Asia have experienced a similar phenomenon. For instance, the amount of CW sent to landfill in South Korea fell by nearly 30% after a landfill charging scheme was introduced in 1995 (Hao et al., 2008) and CW in Taipei fell by approximately 40% after a charging scheme came into operation in 2002 (Tsai & Chou, 2004).

A representative scheme is the CW disposal charging (CWDC) scheme in Hong Kong, which commenced in December 2005 (Yu et al., 2013). After several years of implementation, CWDC is recognized as one of the most influential management approaches for suppressing the negative impacts of CW (Lu & Tam, 2013; Yu et al., 2013).

The philosophy underlying the Hong Kong CWDC scheme is the dichotomy between inert and noninert CW (Lu & Tam, 2013). Inert CW (such as soil, earth, silt, slurry, rocks, and broken concrete) is unreactive, noncombustible, and less odorous, while noninert CW (such as metals, timber, and plastic packaging) creates water, air, and soil pollution. The CWDC scheme is based on this dichotomy and aims to divert inert CW to public filling facilities and relieve the pressure on landfills for the disposal of noninert CW. According to the current CWDC scheme, the disposal of CW should be subject to a charge of HK$200/ton (approximately US$25.64/ton) of waste sent to landfill, HK$175/ton (approximately US$22.34/ton) of waste sent to sorting facilities, and HK$71/ton (approximately US$9.1/ton) of waste sent to public fill reception facilities (Environmental Protection Department of Hong Kong, 2020).

The idea of CWDC is clear, namely, utilizing the price difference between inert and noninert CW disposal to motivate contractors to change their CW disposal behavior. However, Hong Kong's CWDC scheme is still facing challenges. Studies have found that although the CWDC performed well in its first few years, its performance has not been sustained as time has gone on (Lu et al., 2016; Yu et al., 2013). In addition, while the construction sector contributes approximately 3% of GDP, it generates 25% of overall municipal solid waste sent to landfill in Hong Kong (Lu & Tam, 2013). The current CWDC scheme is mainly designed for cost recovery, rather than for pursuing broader environmental protection goals (Mak et al., 2019). Therefore, policymakers face the challenge of refining the CW management scheme and further reducing the negative impact of CW. To tackle this challenge, this paper identifies two major intertwined aspects of the current CWDC scheme that should be further addressed.

The first aspect is the influence of CW transportation. Although the impact of CW is generated during transportation as well as at the disposal stage, the former has attracted little attention (Gálvez-Martos et al., 2018; Maués et al., 2021). CW needs to be transported by heavy, diesel oil–powered trucks, which are a major contributor to greenhouse gas (GHG) emissions. Maués et al. (2021) assessed the GHG emission of the CW transportation process in the Eastern Amazon. They collected data from large CW generators and CW transportation companies and quantified the carbon dioxide (CO_2) equivalents (CO_2eq) emitted in November 2019. They found that approximately 0.9 million kg CO_2 was released into the atmosphere by motor vehicles powered by fossil fuels, contributing considerably to global warming. Heavily loaded trucks also bring safety threats to drivers and other road users and shorten the design life of road surfaces. In addition, the transportation cost is a significant component of the overall CW disposal cost (Lu et al., 2016). Therefore, the impact of CW transportation cannot be ignored.

The second aspect is the behavior of contractors. Although the idea of the CWDC scheme is clear, little research has considered the behavioral characteristics of contractors and the optimal design of the CWDC scheme. Contractors tend to prefer cheaper facilities to save costs. To the best of our knowledge, the CWDC scheme was designed according to the polluter-pays principle (PPP) (Hao et al., 2008; Poon et al., 2013). However, the actual CW disposal cost is a summation of the CW charge and transportation cost. The current CWDC scheme ignores the influence of the CW transportation cost. Lu et al. (2016) reported that the cost of transportation from a site to disposal facilities was significant and could be higher than the disposal levy itself. If the transportation cost is large enough, even though certain facilities charge a lower price, contractors may still prefer using higher priced facilities to minimize their total cost.

Given that the influence of transportation cost and contractor behavior needs to be further explored, a systematic study is necessary to optimize the current CWDC scheme, and this is the main objective of this paper. Specifically, we use a bilevel programming methodology (Hu et al., 2022; Qi & Wang, 2023) to explicitly depict the interaction between contractors and CW managers. Bilevel programming is a type of optimization that contains another optimization problem in the constraints. This formulation is suitable for reflecting hierarchical decision-making processes. That is, the realized decision made by the upper–level authority (leader) to optimize its outcome is affected by the response of lower–level entities (followers), who seek to optimize their own outcomes. Therefore, the bilevel programming scheme is a good fit for this study.

The remainder of this paper is organized as follows. Section 2 summarizes the related literature. Section 3 describes the problem in detail. Section 4 formulates mathematical models and discusses reformulation and linearization techniques. Extensive numerical experiments and a case study are elaborated and reported in Section 5. Conclusions and future research directions are presented in Section 6.

2 | LITERATURE REVIEW

We sketch the research outline of CW management via this section. To identify typical and relevant studies, we search the database of Scopus, Science Citation Index, Google Scholar, and retrieve studies by tracking the references cited in these papers. Table 1 lists these papers, the problem they consider, and the solution approach they use. For a more comprehensive review of CW management, refer to Jin et al. (2019) and Li et al. (2022).

CW is one of the largest solid waste streams (Gálvez-Martos et al., 2018). Considering its high volume and weight, the overall environmental impact is significant. Generally, solutions to deal with CW can be broadly classified into two categories. One is developing new techniques and another is enacting management approaches. New techniques include applying building information modeling–based life cycle assessment approach for sustainable and environmentally conscious building design (Adeli, 2002; Ansah et al., 2021), using recycled concrete aggregate for asphalt pavements (Xu et al., 2022), and construction activities (Zhang et al., 2023). However, the maturity of a new technology is a long process and it cannot achieve success without management supports. In addition, handling CW is not only a technology problem, but also a social issue (Lu & Tam, 2013). Therefore, many efforts are devoted to CW management.

CW management in developed countries and regions has formed a relative systematic policy framework. There are four management levels: preconstruction, construction, demolition, and recycle (Gálvez-Martos et al., 2018). At the preconstruction level, the CW authority makes a plan, such as priorities waste prevention, establish minimum sorting requirements, identify and quantify amounts of CDW, evaluate environmental impacts, as well as regulations and economic drivers, such as subsidies, taxes, levies (Hossain et al., 2017). Construction level is related to site CW reduction, prevention, and material reuse. At the demolition level, the authorities consider building deconstruction, CW sorting, and processing. Recycle management is related to CW treatment and material recovery. No matter what management level is, their objective is consistent, that is, to pursue a sustainable and environment-friendly building industry. These policies work together and form an interlocked CW management system.

In this context, a series of studies focus on investigating the performance of these CW management practices. For example, Gálvez-Martos et al. (2018) synthesize core principles and best practices in Europe for CW management across the entire construction value chain. They find most of observed efforts are devoted to creating drivers for stakeholders in the CW management system and point out the significance of systematic implementation of these best practices. Tam (2008) investigates the effectiveness of a CW management plan in Hong Kong started in 2003 via conducting questionnaire surveys and structured interviews. Then, the benefits and difficulties are identified, possible promoting measures for implementing this plan are also recommended. Wang et al. (2004) develop a spreadsheet-based system analysis model to evaluate the cost–benefit of CW management. Their model is developed to track the CW stream through various stages of the CW process system, that is, generation, sorting, processing, recycling, and disposal. They incorporate the CW flow with the cost/revenue in each management stage, which is expected to provide an economic analysis for a CW management scenario.

Compared with developed countries and regions, studies in developing areas tend to investigate the potential, trends, lessons, challenges, and key factors of CW management practices. Ding and Xiao (2014) estimate the quantification and composition of CW in a fast-developing region, for example, Shanghai, China. They consider structure types and waste intensities at the regional level. The results show the significant economic and environmental benefits of appropriate CW management. Yuan et al. (2022) investigate Chinese CW process system from a broader perspective. They use dissipative structure theory to examine whether the Chinese CW process system

TABLE 1 Summary of literature on construction waste (CW) management.

Paper	Problem and major consideration	Approach
Ansah et al. (2021)	Assessments through all lifecycle phases of a prefabricated building to provide energy and environmental benefits.	Building information modeling-based life cycle assessment method for prefabricated buildings.
Xu et al. (2022)	Use recycled concrete aggregates to substitute natural aggregates in asphalt mixtures.	Review relevant literature and summarizes the potential use of recycled concrete aggregates.
Zhang et al. (2023)	Examine whether innovations currently widely used in construction activities and materials have a positive effect on the recycling of end-of-life concrete materials in China.	System dynamics model.
Gálvez-Martos et al. (2018)	Consider new approaches that take into account the entire value chain of the construction sector.	Synthesize core principles and link best practices for the CW management across the entire value chain.
Tam (2008)	Investigates the effectiveness of the existing implementation of the waste-management-plan method in the Hong Kong construction industry.	Questionnaire survey and structured interviews.
Wang et al. (2004)	Estimate economic impact of policy restrictions on construction contractors and CW processors.	Build a spreadsheet-based systems analysis model to evaluate the cost–benefit of various CW management scenarios.
Ding and Xiao (2014)	Estimate the quantification and composition of building-related CW in a fast-developing region like Shanghai, P. R. China.	Consider the varieties of structure types and building waste intensities.
Yuan et al. (2022)	Examine whether China's CW minimization system is a dissipative structure.	Dissipative structure modeling.
Bao and Lu (2020)	Investigate lessons learned from Shenzhen, China, which has experienced exciting economic growth in the past few decades but also been compelled to rapidly develop an effective CW circular economy from a low base.	A mixed-method approach combining case study, site investigations, and interviews.
Yuan (2017)	Investigate challenges and promise countermeasures of managing CW in a typical economically developed region of Shenzhen in south China.	Review of literature, government regulations and reports, semistructured interviews, and group discussions with governmental staff and industry participants.
Wu et al. (2017)	Investigate the determinants of the contractor's CW management behavior in Mainland China.	Theory of planned behavior.
Chen et al. (2019)	Describe the decision-making behaviors of major participants in CW management.	Evolutionary game.
Hao et al. (2007) and Hao et al. (2008)	Examine the effectiveness of the Hong Kong CWDC scheme after 1 year of implementation in particular "polluter pays principle."	Survey at sites to record daily CW from landfills and public filling facilities.
Yu et al. (2013)	Investigate the changes in reducing CW generation practice among construction participants in various work trades.	Structured questionnaire survey in the building industry.
Poon et al. (2013)	Investigate perceptions of the Hong Kong construction participants toward the CWDC scheme after 3 years of implementation.	Survey with follow-up interviews to experienced professionals in the building industry.
Lu and Tam (2013)	Examine the effectiveness of a series of CW management policies in Hong Kong.	Longitudinal study.
Li et al. (2020)	Find the tipping point that the stakeholders will change their waste handling behavior.	Contingent valuation method.
Yuan and Wang (2014)	Determine an appropriate CW disposal charging fee in the construction sector for reducing CW generation, propose recycle, and control illegal dumping.	System dynamics model.
Jia et al. (2017)	Simultaneously use penalty, CW disposal charging, and subsidy to manage dumping.	System dynamics model.

(Continues)

TABLE 1 (Continued)

Paper	Problem and major consideration	Approach
Mak et al. (2019)	Determine an appropriate CW disposal charging fee for sustainable development needs.	System dynamics model.
Liu et al. (2022)	Investigate economic benefits of CW recycling enterprises under tax incentive policies.	System dynamics model.
Hua et al. (2022)	Promote subsidy and environmental tax policies to promote CW recycling.	System dynamics model.
Cheng et al. (2022)	Investigate how government incentives and punishments improve contractors' participation in resource utilization of CW.	System dynamics model.
Wei et al. (2022)	Investigate freight characteristics and carbon emission of CW hauling trucks.	Big data analysis.

is a dissipative structure. Suggestions are provided to promote the CW process system toward a dissipative structure. Yuan (2017) explores the challenges of managing CW in the fast-developing Shenzhen. Data are collected via literature, regulations, reports, semistructured interviews, and group discussion with governmental staff and industry participants. Five drawbacks and four countermeasures are presented to help form an interlocked CW management framework. Bao and Lu (2020) report lessons learned from a rapid growing city, that is, Shenzhen, China. They adopt a mixed investigation method that combines case study, site investigations, and interviews. The identified that success factors are government interventions, market cultivating, advanced technology introduction, and institutional arrangements. Wu et al. (2017) discuss the key factors of the contractors' CW management behavior in the context of mainland China. A planned behavior-based theoretical model is built. They collect data from questionnaire survey, test the hypotheses via a structural equation modeling analysis, and find that the most important factors are economic viability and governmental supervision, rather than construct constraint. Chen et al. (2019) investigate the interaction between contractors' behavior and government's CW policy. An evolutionary game model is established, which considers supervisory intensity, supervision costs, penalties, CW disposal costs, and revenues from illegal dumping. They demonstrate only raising the penalty without maintaining supervision at a proper level is ineffective.

No matter the research topics, the majority of above studies acknowledge that economic leverage is one of the most effective approaches to management CW. As early as 1999, most European Union members applied landfill charges. For instance, in Berlin, Germany, disposing of unsorted CW to landfill is charged 86 Euro per cubic meter, while sorted CW, such as concrete, brick, and tile costs 53 euros per cubic meter (Li et al., 2018). Gálvez-Martos et al. (2018) summarize the best CW management practices in Europe and the economic instruments are recognized as an effective tool to adjust contractors' CW disposal decisions. In the United States, San Jose adopt the CWDC scheme, which requires a contractor to pay for CW disposal when it gets a new construction permit (Poon et al., 2013).

In this situation, there is also a research line that focuses on investigating economic incentives or punishment. Hao et al. (2007, 2008) examine the effectiveness of the Hong Kong CWDC scheme after 1 year of implementation via a survey at the CW disposal facilities. Daily CW records are collected from different types of facilities, that is, landfill and public fill, from January to December 2006. They demonstrate that CW generation has been effectively restrained. Lu and Tam (2013) examine the effectiveness of the Hong Kong CW management policies via a longitudinal study. It is found that the CWDC scheme has the largest magnitude in terms of reducing CW and the government is actively updating its policies based on latest CW management philosophies, for example, PPP. A relatively efficient and interlocked policy system has formed in Hong Kong. However, they also point out that new initiatives are required to change the gloomy situation after the efficient implementation of the CWDC scheme since 2006. Lu et al. (2015) evaluate the willingness to pay for CW management in Hong Kong. They use the economic technique of contingent valuation method and find that the average maximum willingness to pay is higher than the existing CW disposal charges, but still much lower than the charges expected by the government. Li et al. (2020) examine contractor attitudes toward the Hong Kong CWDC scheme and find that contractors' willingness to pay is higher than the current charging standard.

Compared with the CWDC assessment studies (Hao et al., 2008; Poon et al., 2013; Yu et al., 2013), the CWDC scheme design received little attention in the literature. Yuan and Wang (2014) point out that the majority of previous CWDC schemes implemented in China are determined based on a rule of thumb, in which effectiveness is very limited. Therefore, they propose a system dynamics model to optimally determine the charging fee. Their work is the first attempt to employ a simulation-based model to depict the interaction between major variables in the CW disposal system. Jia et al. (2017) investigate the effects of penalty and subsidy mechanisms on illegal dump, CW recycle, and reuse. The system dynamics approach is used to determine a reasonable penalty range. They suggest a combination of penalty and subsidy is capable of effectively alleviating the problems associated with CW management. Mak et al. (2019) argue that most of the existing CWDC schemes are designed for cost recovery, rather than for CW reduction and environmental protection. Therefore, they develop an elaborated system dynamics model to evaluate the interactions of the system in CW disposal charges. Their simulation results indicate that the current CWDC scheme in Hong Kong is ineffective in the long term and the optimum increment percentage of landfill and public fill fee should not exceed 250% and 400%, respectively. Liu et al. (2022) evaluate the role of tax incentive in promoting CW recycling in the aspect of economic impact. They use the system dynamics method and take the tax incentive in Guangzhou city as an example to build a tailored model. They recommend the appropriate tax intensive range, estimate the possible revenue, cost of enterprises, and provide policy suggestions, such as increase tax incentives, add equipment tax incentive policies, change tax mode, and so forth. Hua et al. (2022) point out that although several policies have been issued to promote CW reduction and recycling, the recycling ratio is still low in China. Therefore, they propose an integrated subsidy and tax approach to stimulate the CW recycling industry in China. They also use the system dynamics method to determine the subsidy and environmental tax threshold. Similarly, Cheng et al. (2022) try to improve CW utilization through incentives and punishment. They develop a system dynamics–based simulation model that considers subsidizing CW utilization, increasing landfill fee, and punishment for illegal dumping.

Although many efforts have been devoted to optimize a given CWDC scheme, novel mechanism, considerations, and methods are still limited to enhance its effectiveness and tackle new challenges.

First, most of the studies focus on optimizing the charging fees, for example, public fill and landfill price, while ignoring reforming the charging mechanism. Specifically, these studies are established on a given CWDC scheme and then, search an appropriate charging fee by considering more factors and specific scenarios. However, the current CW charging mechanism is insufficient to achieve green and sustainable building objectives. Many studies have demonstrated this point. Therefore, this paper reforms the existing charging mechanism (i.e., drive contractors change their CW disposal behavior), refine the CWDC scheme, and optimize the charging fees.

Second, existing studies ignore the GHG emission on the road. However, this impact of CW transportation is nonnegligible. Wei et al. (2022) point out that there are many CW hauling trucks in operation and impose massive impact on the city's natural environment and transportation in Hong Kong. It is estimated that 307.64 tons CO_2eq emitted on working days and 28.78 tons CO_2eq on non-working days. Emission amount is related to the vehicle type, CW weight, and trip length, in which trip length is the most influential factor. Therefore, this paper takes CW transportation into consideration. We strive to guide contractors' CW disposal decision to control the pollutants generated at both transportation and disposal stages.

Third, almost all studies employ a simulation-based approach to evaluate and determine the charging fees, for example, system dynamics. Although their research is more elaborated, the interactions between the elements in the simulation system are modeled in an inexplicit way. By comparison, operations research method explicitly depicts the interaction between players in the system. The established model is explicable and the solution results clearly reflect analytical insights. Therefore, to bridge this gap, we employ the bilevel programming approach to optimize the charging scheme and provide insights to better deal with environmental protection challenges.

We note that optimization models have been widely applied to civil and construction fields, such as transportation management (Akhand et al., 2020; Chai et al., 2022; Tang & Zeng, 2022), traffic assignment (Li et al., 2021; Verstraete & Tampère, 2022; Zhang et al., 2021), vehicle route design (Liu et al., 2021; Tong et al., 2021), structure monitoring (Eltouny & Liang, 2021; Sajedi & Liang, 2022), construction surveillance and control (Gutierrez Soto & Adeli, 2018; Miralinaghi et al., 2021; Sanchez et al., 2022; Yi & Sutrisna, 2021), construction cost estimation (Adeli & Wu, 1998; Karim & Adeli, 1999), resource scheduling (Rafiei & Adeli, 2018; Senouci & Adeli, 2001), and freeway project design (Jiang & Adeli, 2003; Karim & Adeli, 2003; Miralinaghi et al., 2020). We extend the research field by applying a bilevel modeling approach to the CW disposal process.

2.1 | Objectives and contributions

This study aims to propose a methodology to optimize the CWDC scheme and elaborate the current CWDC scheme to better manage CW disposal. The contribution of this study is threefold.

First, we propose a refined CWDC scheme to tackle the challenges faced by current scheme in practice. The new scheme is proposed to pursue environment-friendly and sustainable building industry, which allows policymakers to not only consider the environmental issue at CW disposal facilities, but also consider the pollutant discharged during transportation. Policymakers could better adjust contractors' CW disposal behavior through the improved CWDC scheme.

Second, we develop a mathematical model for the optimal design of CWDC scheme. The established model is a bilevel programming problem, which could explicitly reflect the interaction between contractors and authorities. To efficiently address this model, we propose a reformulation, which converts the lower–level problem into a set of constraints. The resulting model is a single-level programming problem, which enables efficient solution approaches to address. Intensive numerical experiments and a real-world case study are conducted to verify the effectiveness of the proposed CWDC schemes.

In addition, to further enhance the innovation of our study, we introduce a new pricing strategy (i.e., the pricing decisions are made for each individual CW disposal facility), which is ignored in existing studies. The extended scheme provides more opportunities to adjust/guide the contractors' behavior and could be more powerful to manage CW. The results reveal that a slight modification of existing CWDC scheme has the potential to significantly improve the function of the CW management practices, which is the practical contribution of our work.

3 | PROBLEM DESCRIPTION

We consider the CW disposal system in the background of Hong Kong, which consists of a set of CW disposal facilities J and a set of contractors K. According to the Hong Kong CWDC scheme (Environmental Protection Department of Hong Kong, 2020), the EPD provides three types ofCW disposal facilities: public fill reception facilities, sorting facilities, and landfills/outlying island transfer facilities. Therefore, the set of CW disposal facilities J is classified into three types, represented by sets J_1, J_2, J_3, $J_1 \cap J_2 = \emptyset$, $J_1 \cap J_3 = \emptyset$, $J_2 \cap J_3 = \emptyset$, $J_1 \bigcap J_2 \bigcap J_3 = J$. Then, the set of CW disposal facility types I is set as $I := \{1, 2, 3\}$. The first type disposes of entirely inert CW, the second type disposes of CW with more than 50% inert components, and the third type disposes of CW with any percentage of inert components. Then, each contractor $k \in K$ has its own available CW disposal facility type set $I_k \subseteq I$ to use. Specifically, contractors who generate entirely inert CW can dispose its wastes at any type of facilities, that is, $I_k = I$. Contractors who generate CW containing more than 50% inert components can dispose their waste at type 2 and 3 facilities, that is, $I_k = \{2, 3\}$. Contractors who generate CW containing less than half inert components can dispose their waste only at type 3 facility, that is, $I_k = \{3\}$. Figure 1 presents an illustrative CW disposal example, which consists of three types of CW disposal facilities and three contractors. Each facility type contains one member in it, that is, F1, F2, and F3. Contractor 1 (C1) generates entirely inert CW, thus, its waste can be accepted by any type of facilities. Similarly, contractor 2 (C2)'s waste can be accepted by F2 and F3, and contractor 3 (C3)'s waste can be accepted by F3.

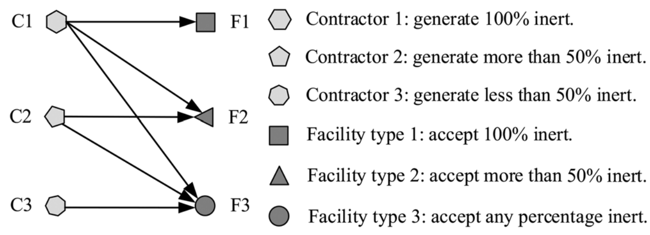

FIGURE 1 An illustration of construction waste (CW) disposal structure.

The contractors are required to transport their generated CW from a construction site k to a selected CW disposal facility j belonging to type i. Let c_{ijk} denote the transportation cost per ton between k and $j \in J_i$, $i \in I_k$, and x_i denote the charging fee per ton of CW at type i's CW disposal facilities. Contractors make decisions according to their total cost, which is a combination of transportation cost c_{ijk} (per ton) and CWDC fee x_i (per ton), that is, $c_{ijk} + x_i$. The contractors choose the CW disposal facility to minimize their total cost. Then, we have the following principle.

Principle 1. *Only the facility $j \in \tilde{J}_i \subseteq J_i$ can be selected by contractor $k \in K$ if and only if the set $\tilde{J}_i$ is the minimal total cost choices among all candidates $J_i, i \in I_k$ for this contractor.*

Generally, the transportation cost from k to j cannot be significantly changed since the transport network is given. Transport infrastructure construction is a long-term project and a huge investment. By comparison, the pricing x_i is changeable, which can be determined by the government agencies (we use the EPD of Hong Kong to refer to the government agency hereafter). The major environmental pollution of CW comes from two aspects, that is, transportation stage and disposal stage. The CW, loaded by heavy dump trucks generates GHG and noise pollution, brings safety threats to road users, and reduces the life of road pavement (Maués et al., 2021). The CW at disposal facilities generates air, water, and visual pollution, destructs soil structure, and increases the risk of fires

(Sauve & Van Acker, 2020). Let e_{ijk} be a value to quantify the environmental impact of transporting one ton of CW from k to $j \in J_i$, $i \in I_k$, and h_i be a value to quantify the environmental impact of disposing one ton of CW at type i's CW disposal facilities. Then, EPD needs to reduce the overall environmental impact of CW, which is related to the sum of e_{ijk} and h_i, that is, $e_{ijk} + h_i$. Therefore, we have the following principle.

Principle 2. *EPD expects contractors to choose the facility $j \in \hat{J}_i \subseteq J_i$, where the set $\hat{J}_i$ is the facilities with minimal total environmental effects among all candidates $J_i, \forall i \in I_k$, $k \in K$.*

The objectives of EPD and contractors are inconsistent. Contractors would not follow EPD's expectations unless their objectives happen to be consistent. Therefore, the value of CW pricing should not only reflect EPD's expectations but also be treated as a management tool to adjust contractors' facility selection behavior. The EPD, therefore, needs to decide the price x_i, $i \in I$, and to reduce negative environmental impacts of CW.

Moreover, we note that not only the price value can be optimized, the pricing scheme itself can also be extended to better achieve the environmental protection objective. The current pricing scheme is designed based on the facility type. Therefore, it cannot change contractors' behavior among the same type of facilities. To address this issue, we further extend the current pricing scheme to allow each facility to charge a tailored price, that is, x_{ij}, $i \in I$, $j \in J_i$, where i denotes the facility type and j denotes a specific CW disposal facility. Using the tailored price x_{ij}, the EPD has more flexibility to change contractors' behavior. The specific mathematical models to search optimal x_i and x_{ij} are proposed in the next section.

4 | MODEL FORMULATION

In this section, we propose two mixed-integer programs for the optimal design of CWDC schemes. The notion for describing the models are listed in Section 4.1; Section 4.2 presents bilevel mixed-integer programming models (Wang et al., 2022a, 2022b) for the optimal design of CWDC fee; Section 4.3 reformulates these models and transforms them into single-level mixed-integer programming models; Section 4.4 describes linearization techniques to further transform them into mixed-integer linear programming models, which enable a variety of off-the-shelf solvers to address (Zavadskas et al., 2016).

4.1 | Notations

Sets and indexes:

- I: set of CW disposal facility types;
- i: index for CW disposal facility type;
- J: set of CW disposal facilities;
- J_i: set of CW disposal facilities that belong to type i;
- j: index for CW disposal facility;
- K: set of contractors/construction sites;
- k: index for contractors;
- I_k: set of types of CW disposal facilities suitable for contractor k.

Input parameters:

- c_{ijk}: transportation cost of one ton of CW from contractor k to CW disposal facility j that belongs to type i;
- e_{ijk}: environmental impact index of transportation one ton of CW from contractor k to CW disposal facility j that belongs to type i;
- h_i: environmental impact index of disposing one ton of construction waste in facilities of type i;
- v_k: the weight (ton) of CW generated at construction site k;
- $\bar{x}$: upper charging bound per tonne of CW at a CW disposal facility;
- $\underline{X}$: minimal charging target for the whole system.

Decision variables:

- x_i: CW disposal charging fee per ton of CW for facilities that belongs to type i (x_i is used in the basic model);
- x_{ij}: CW disposal charging fee per ton of CW for facility j that belongs to type i (x_{ij} is used in the extended model);
- z_{ijk}: binary decision variable to indicate the decision of construction site k concerning the facility type i and candidate facility j; z_{ijk} is 1 if k decides to let j belonging to type i dispose CW and 0 otherwise.

4.2 | Mathematical model

In this section, we build mathematical models to optimally manage the transportation of CW. We first consider the facility type–based pricing scheme, in which a unified price is provided for CW disposal facilities belonging to the same type. Then, we extend this scheme to a more general scenario that each facility has its customized waste disposal price, that is, the facility-based pricing scheme.

4.2.1 | Basic model

We first build the lower level model to reflect the contractors' facility choice behavior and then propose a bilevel programming model to optimally design CWDC scheme, in which contractors' facility choice is considered and incorporated into the bilevel structure (Qu, Wang, et al., 2022; Qu, Zeng, 2022).

The contractors aim to select some appropriate waste disposal facilities to dispose their generated CW. Recall that I denotes the set of CW disposal facility types and i denotes a specific CW disposal facility type, $i \in I$; J_i denotes the set of CW disposal facilities belonging to type i, and j denotes a specific CW disposal facility, $j \in J_i$; K denotes the set of contractors. For a specific construction site $k \in K$, it would select a CW disposal facility j to dispose its generated CW from the CW disposal facility subset J_i, $i \in I_k \subseteq I$. Let z_{ijk} be a binary decision variable and $\mathbf{z} := \{z_{ijk}, \forall i \in I, j \in J_i, k \in K\}$. z_{ijk} equals 1 if k decides to let j belonging to type i dispose CW, and 0, otherwise. Then, this condition can be expressed as follows.

$$\sum_{i\in I}\sum_{j\in J_i} z_{ijk} = 1, \forall k \in K \quad (1)$$

$$z_{ijk} = 0, \forall i \in I \backslash I_k, j \in J_i, k \in K \quad (2)$$

$$z_{ijk} \in \{0, 1\}, \forall i \in I, \ j \in J_i, \ k \in K \quad (3)$$

where Equation (1) means a construction site k could select only one CW disposal facility. Equation (2) implies that it is not allowed to select a CW disposal facility that is not available for CW generated at k. In other words, CW at k may be only suitable for some specific CW disposal facilities. Equation (3) defines the domain of z_{ijk}. Equations (1)–(3) define the feasible region Ω of $\mathbf{z}$. As per Principle 1, the objective of contractor is to minimize its CW disposal payment, which includes transportation cost c_{ijk} and the CWDC fee x_i. Let $\mathbf{x}$:=$\{x_i, \forall i \in I\}$. Then, the CW disposal facility choice model can be written as follows.

$$[\text{M1}] \ \min_{\mathbf{z}\in\Omega} Z_1 \ (\mathbf{x}, \mathbf{z}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} \left(c_{ijk} + x_i\right) v_k z_{ijk} \quad (4)$$

where Z_1 represents the total payments of all contractors K.

As per Principle 2, the EPD aims to design an optimal CWDC scheme to protect the city environment. The environmental impact comes from the transportation and the CW disposal process, which further depends on contractors' choice, that is, $\mathbf{z}$. EPD cannot directly command the contractors to minimize the environmental effect, however, it can influence contractors' behavior through CW disposal pricing. The contractors have the freedom to select any CW disposal facility to dispose their CW, while the EPD has the right to determine the CW disposal price. This interaction between EPD and contractors falls into the category bilevel programming problem. The contractors' facility choice behavior is modeled by a lower–level problem and incorporated into the upper–level programming. Specifically, this bilevel programming model can be formulated as follows.

$$[\text{M2}] \ \min Z_2 (\mathbf{x}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} \left(e_{ijk} + h_i\right) v_k z^*_{ijk} \quad (5)$$

subject to

$$x_i \geq 0, \forall i \in I \quad (6)$$

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k x_i z^*_{ijk} \geq \underline{X} \quad (7)$$

$$x_i \leq \bar{x}, \forall i \in I \quad (8)$$

$$\mathbf{z}^* \in \underset{\mathbf{z}\in\,\Omega}{\operatorname{argmin}} \ Z_1 (\mathbf{x}, \mathbf{z}) \quad (9)$$

Objective (5) minimizes the total environmental impact produced by contractors. Constraint (6) is the nonnegative constraint for the CW disposal pricing variable x_i. Constraint (7) requires that the total revenue for EPD should be no less than a given threshold $\underline{X}$. The reason of setting a minimal charging target is for cost recovery. Daily CW disposal operation requires sustaining investment and CW charging could at least cover a part of operation cost. Constraint (8) requires that x_i does not exceed a given threshold $\bar{x}$. Constraint (9) reflects the contractors' decision concerning EPD's CWDC scheme.

We note that decision variables $\mathbf{x}$ are not directly contained in the objective function (5). Because EPD's objective is to pursue environmental protection, rather than make profit. Pricing is taken as a management approach to affect contractors' behavior. Subsequently, different behavior results into different pollution levels. The EPD's objective is to minimize the total pollutant discharged during CW disposal in the city/region level. In other words, $\mathbf{x}$ adjusts contractors' decision $\mathbf{z}$ and indirectly decides the pollution level. Therefore, the objective function is defined in this way.

4.2.2 | Extended model

We proceed to generalize the basic CWDC scheme presented in Section 4.2.1, by customizing the CW disposal price for each specific facility. To achieve this goal, we extend both [M1] and [M2]. First, the CW disposal facility choice model in this scenario is written as:

$$[\text{M3}]\ \min_{\mathbf{z}\in\Omega} Z_3\ (\mathbf{x},\mathbf{z}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(c_{ijk} + x_{ij}\right) v_k z_{ijk} \quad (10)$$

With a little abuse of notion, we still use $\mathbf{x}$ hereafter for the facility-based CWDC scheme. [M3] gives contractors more flexibility to choose their suitable CW disposal facility to minimize their payments.

Then, the bilevel programming model for the optimal CW disposal price design can be formulated as:

$$[\text{M4}]\ \min Z_4\ (\mathbf{x}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(e_{ijk} + h_i\right) v_k z^*_{ijk} \quad (11)$$

subject to

$$x_{ij} \geq 0, \forall i \in I, j \in J_i \quad (12)$$

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k x_{ij} z^*_{ijk} \geq \underline{X} \quad (13)$$

$$x_{ij} \leq \bar{x}, \forall i \in I, j \in J_i \quad (14)$$

$$\mathbf{z}^* \in \underset{\mathbf{z}\in\ \Omega}{\text{argmin}}\ Z_3\left(\mathbf{x},\mathbf{z}\right) \quad (15)$$

where objective (11) minimizes the total environmental impact produced by contractors. Constraint (12) requires CW disposal pricing variable x_{ij} to be nonnegative. Constraint (13) ensures the total revenue to be larger or equal to a given threshold $\underline{X}$. Constraint (14) requires that x_{ij} does not exceed a given threshold $\bar{x}$. Constraint (15) defines the contractors' facility choice behavior. With [M4], each facility has its own suitable CW disposal price to better achieve the goal of minimizing the environmental impact.

4.3 | Model reformulation

To solve our proposed bilevel programming models, in this section, we transform [M2] and [M4] into single-level optimization models.

Recall that [M1] reflects facility choice behavior of contractors who always choose the facility to minimize their transportation and CW disposal cost. In other words, for a given construction site k, if this contractor decides to transport its CW to facility j, that is, $z_{ijk} = 1$, then the transportation and CW disposal cost should satisfy the following condition:

$$c_{ijk} + x_i \leq c_{i'j'k} + x_{i'}$$

$$\forall i' \in I_k,\ j' \in J_{i'},\ ij \neq i'j' \quad (16)$$

Conversely, if $z_{ijk} = 0$, condition (16) does not necessarily hold. Let $M_k = \max(c_{ijk} + \bar{x}, \forall i \in I_k,\ j \in J_i)$ be a "large" constant, then the facility choice behavior of a construction site k is equivalent to the following condition:

$$c_{ijk} + x_i - M_k\left(1 - z_{ijk}\right) \leq c_{i'j'k} + x_{i'}$$

$$\forall i' \in I_k,\ j' \in J_{i'}, ij \neq i'j' \quad (17)$$

Condition (17) means if z_{ijk} equals 1, the corresponding transportation and CW disposal cost between construction site k and facility j is minimal among all candidate CW disposal facilities. In this way, [M1] can be transformed into a group of inequalities. Then, the bilevel programming model [M2] can be reformulated as:

$$[\text{M5}]\ \min Z_2\left(\mathbf{x}\right) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(e_{ijk} + h_i\right) v_k z_{ijk} \quad (18)$$

subject to

$$x_i \geq 0, \quad \forall i \in I \quad (19)$$

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k x_i z_{ijk} \geq \underline{X} \quad (20)$$

$$x_i \leq \bar{x}, \quad \forall i \in I \quad (21)$$

$$\sum_{i\in I}\sum_{j\in J_i} z_{ijk} = 1, \quad \forall k \in K \quad (22)$$

$$c_{ijk} + x_i - M_k\left(1 - z_{ijk}\right) \leq c_{i'j'k} + x_{i'}$$

$$\forall i, i' \in I_k,\ j \in J_i,\ j' \in J_{i'},\ k \in K, ij \neq i'j' \quad (23)$$

$$z_{ijk} = 0, \quad \forall i \in I \backslash I_k, j \in J_i, k \in K \quad (24)$$

$$z_{ijk} \in \{0, 1\}, \quad \forall i \in I,\ j \in J_i,\ k \in K \quad (25)$$

With the above reformulation, [M2] becomes a single-level programming model, which is an intermediate step in developing the solution approach (Wang et al., 2017, 2018; Zhen et al., 2020).

Similarly, in the extended contractors' facility choice model [M3], for a given construction site k, if this contractor decides to transport its CW to facility j, that is, $z_{ijk} = 1$, the following condition should be satisfied:

$$c_{ijk} + x_{ij} \leq c_{i'j'k} + x_{i'j'}$$

$$\forall i' \in I_k,\ j' \in J_{i'},\ ij \neq i'j' \tag{26}$$

Conversely, if $z_{ijk} = 0$, condition (26) does not necessarily hold. Then, the facility choice behavior of a construction site k is equivalent to the following condition:

$$c_{ijk} + x_{ij} - M_k\left(1 - z_{ijk}\right) \le c_{i'j'k} + x_{i'j'}$$

$$\forall i' \in I_k,\ j' \in J_{i'}, ij \neq i'j' \tag{27}$$

Condition (27) means if z_{ijk} equals 1, facility j is the optimal choice for contractor k. Then, the bilevel programming model [M4] can be transformed as:

$$[\text{M6}]\ \min Z_4\ (\mathbf{x}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(e_{ijk} + h_i\right) v_k z_{ijk} \tag{28}$$

subject to

$$x_{ij} \ge 0, \quad \forall i \in I, j \in J_i \tag{29}$$

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k x_{ij} z_{ijk} \ge \underline{X} \tag{30}$$

$$x_{ij} \le \bar{x}, \quad \forall i \in I, j \in J_i \tag{31}$$

$$\sum_{i\in I}\sum_{j\in J_i} z_{ijk} = 1, \quad \forall k \in K \tag{32}$$

$$c_{ijk} + x_{ij} - M_k\left(1 - z_{ijk}\right) \le c_{i'j'k} + x_{i'j'}$$

$$\forall i, i' \in I_k,\ j \in J_i,\ j' \in J_{i'},\ k \in K, ij \neq i'j' \tag{33}$$

$$z_{ijk} = 0, \quad \forall i \in I \backslash I_k, j \in J_i, k \in K \tag{34}$$

$$z_{ijk} \in \{0, 1\}, \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{35}$$

[M6] is a single-level programming model.

4.4 | Model linearization

Converting [M2], [M4] into [M5], [M6] is not the end of reformulation, [M5] and [M6] are still difficult to solve because constraints (20) and (30) are nonlinear (Wang et al., 2021; Zhen et al., 2019). To address this issue, we introduce a set of intermediate variables $\{y_{ijk}, \quad \forall i \in I,\ j \in J_i,\ k \in K\}$. Then, constraints (20) can be linearized as:

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k y_{ijk} \ge \underline{X} \tag{36}$$

$$y_{ijk} \le \bar{x} \cdot z_{ijk}, \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{37}$$

$$y_{ijk} \le x_i, \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{38}$$

$$y_{ijk} \ge x_i - \bar{x} \cdot \left(1 - z_{ijk}\right)$$

$$\forall i \in I,\ j \in J_i,\ k \in K \tag{39}$$

$$y_{ijk} \in [0, \bar{x}], \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{40}$$

Then, [M5] is equivalent to:

$$[\text{M7}]\ \min Z_2\ (\mathbf{x}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(e_{ijk} + h_i\right) v_k z_{ijk} \tag{41}$$

subject to constraints (19), (21)–(25), and (36)–(40).
Similarly, constraints (30) can be linearized as:

$$\sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K} v_k y_{ijk} \ge \underline{X} \tag{42}$$

$$y_{ijk} \le \bar{x} \cdot z_{ijk}, \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{43}$$

$$y_{ijk} \le x_{ij}, \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{44}$$

$$y_{ijk} \ge x_{ij} - \bar{x} \cdot z_{ijk}$$

$$\forall i \in I,\ j \in J_i,\ k \in K \tag{45}$$

$$y_{ijk} \in [0, \bar{x}], \quad \forall i \in I,\ j \in J_i,\ k \in K \tag{46}$$

Then, [M8] is equivalent to:

$$[\text{M8}]\ \min Z_4\ (\mathbf{x}) = \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\left(e_{ijk} + h_i\right) v_k z_{ijk} \tag{47}$$

subject to constraints (29), (31)–(35), and (42)–(46).

4.5 | Further discussion

The proposed models represent a new methodology for the optimal design of CWDC scheme. Along this way, more scenarios can be incorporated into this modeling framework to establish an integrated model and better manage CW disposal process.

In this section, we consider one possible extension. Note that in some regions, building demolition methods could be various. Different demolition methods may lead to various induced demolition costs, because the possible reuse and recycle methods are different. Therefore, contractors' choice of demolition method could be taken into account. The induced cost during demolition is taken as a part of the whole CW disposal cost. This study provides a general framework that is extendable to this situation.

Specifically, let L denote the set of demolition methods and l denote one alternative belong to L. The demolition fee is denoted as c_l. Then, we introduce another binary variable z_{lk}. z_{lk} equals 1 if contractor k selects l to demolish old buildings, and 0, otherwise. Let $\bar{\mathbf{z}}$:=$\{z_{lk}, \quad \forall l \in L, k \in K\}$. Only one demolition method can be chosen, therefore, we have:

$$\sum_{l \in L} z_{lk} = 1, \quad \forall k \in K \tag{48}$$

$$z_{lk} \in \{0, 1\}, \quad \forall l \in L, k \in K \tag{49}$$

where Equation (48) means a contractor k could select only one demolition method. Equation (49) defines the domain of z_{lk}. Equations (48)–(49) define the feasible region $\bar{\Omega}$ of $\bar{\mathbf{z}}$. The objective of the contractor is to minimize its CW demolition and disposal cost, which includes demolition fee c_l, transportation cost c_{ijk}, and the CWDC fee x_i. Then, the contractors' decision model can be written as:

$$[\text{M9}] \quad \min_{\mathbf{z} \in \Omega, \bar{\mathbf{z}} \in \bar{\Omega}} Z_5\,(\mathbf{x}, \mathbf{z}) = \sum_{i \in I} \sum_{j \in J_i} \sum_{k \in K} \left(c_{ijk} + x_i\right) v_k z_{ijk} + \sum_{l \in L} \sum_{k \in K} c_l v_k z_{lk} \tag{50}$$

where Z_5 represents the total payments of all contractors K. [M9] not only considers contractors' CW disposal facility choice, but also considers contractors' demolition method selection. Then, [M9] is able to substitute [M1] or [M4] for the optimal design of CWDC scheme when necessary.

5 | NUMERICAL EXPERIMENTS

Extensive computational experiments and a case study are performed. The numerical experiments are carried out on an AMD Core 4800H 2.9 GHz PC with 16G RAM. Gurobi 9.1.2 is used as the mixed-integer linear programming model solver for these instances. We note that the parameters are randomly generated in the experiments to obtain some insights. The specific parameter could be calibrated according to measured and surveyed data in the real world.

5.1 | Illustrative example

An illustrative example of a small number of construction sites and waste disposal facilities is calculated to demonstrate the research methodology.

TABLE 2 Description of available facility type.

Waste disposal facility type	Type of construction waste (CW) acceptable	Current charge per ton ($)	Env impact per ton
1	Entirely inert CW	7	10
2	Containing more than 50% by weight of inert CW	18	20
3	Containing any percentage of inert CW	20	40

5.1.1 | Parameters

In this illustrative example, there exist three types of waste disposal facilities. Type 1 facilities dispose entirely inert CW, Type 2 facilities dispose CW with more than 50% inert CW by weight, and Type 3 facilities dispose CW with any percentage of inert CW. Table 2 shows the attributes of the three facility types, that is, the acceptable CW type, current charging pattern ($), and environmental impact index of disposing one ton CW. The benchmark charging scheme is estimated based on the Hong Kong CWDC scheme in which the charging fee for facility types 1, 2, 3 is set as 71($), 175($), 200($), respectively. Their ratio is approximately 7: 18: 20. Therefore, in the illustrative example, we keep this ratio and set the benchmark charging fee to obtain some insights.

The current waste disposal research does not consider the influence of transportation. Li et al. (2020) reveal that the contractors' willingness to pay is higher than the current charging standard, which implies the environmental impact of CW is significant, Therefore, we assume one unit of environmental impact is equivalent to one unit of price for the convenience of comparison. The detailed conversion rate can be calibrated using surveyed/measured data from EPD and construction sectors. The specific of CW does not influence contractors' facility selection decisions. Therefore, we assume that each contractor generates the same amount of CW to obtain some insights. The environmental impact indexes are set as 10, 20, and 40 for type 1, 2, and 3 facilities according to the following two considerations: (i) the environmental impact of disposing CW at type 1 facilities should be less than type 2 facilities, which should be further less than type 3 facilities, and (ii) the environmental impact of disposing inert CW is higher than noninter CW.

Table 3 lists construction sites, CW disposal facilities, their transportation cost, and environmental impact (GHG emission, noise pollution, etc.) during transportation. Generally, there are three construction sites. Construction site 1 generates entirely inert CW, which can be disposed by

TABLE 3 Description of transportation costs and environmental impact.

Construction site	Facility type	Facility	Transportation cost per ton ($)	Env impact per ton
1	1	1	3	33
		2	15	47
		3	19	29
	2	1	2	45
		2	18	20
		3	21	10
	3	1	29	6
		2	2	4
		3	13	32
2	2	1	26	12
		2	21	47
		3	4	50
	3	1	12	3
		2	7	43
		3	4	28
3	3	1	21	4
		2	3	35
		3	10	50

any type of CW disposal facility. Construction site 2 generates CW with more than 50% by weight of inert CW, which could only be transported to facilities belonging to types 2 and 3. Construction site 3 generates waste that contains less than 50% by weight of inert CW, which could only be transported to facilities belonging to type 3. Note that the locations of disposal facilities are not the same. For example, the location of facility 1 belonging to type 1 is different from the location of facility 1 belonging to type 2.

For each facility type, there are three CW disposal facilities. The corresponding transportation cost ($) and environmental impact index during transportation are generated within the range [3, 30] and [3, 50], respectively. The transportation cost and environmental impact are different from each other, because the location of construction sites is different. Some construction sites are close to a few CW disposal facilities, while others may be far away. In addition, the transportation cost is also related to CW type, hauling truck type, and so forth. Therefore, different conditions lead to different transportation costs and environmental impacts.

5.1.2 | Solution analyses

The pricing upper bound for each type of CW disposal facility is set to be 40, that is, $\bar{x} = 40$.

We first examine the situation without the constraint of minimal charging target. In this way, we can preliminarily examine the correctness of the solutions. Meanwhile, we can better illustrate the role of the proposed CWDC scheme by comparing the solution between the status quo, with, or without minimal charging target. The optimal charge fees per ton are $x_1 = 0$ ($), $x_2 = 40$ ($), $x_3 = 40$ ($). The calculated objective value for the EPD is 186. More details are shown in Table 4. In the table, the optimal charges are presented in the column "Charge per ton." Then, the contractor's total CW disposal cost is an addition of transportation cost and CWDC fee, that is, $c_{ijk} + x_i$, which is presented in the column "Contractor's total cost." The contractors' facility choice decision is presented in the column "Contractor's choice." The total environmental impact comes from CW disposal and transportation stages, that is, $e_{ijk} + h_i$, which is shown in the column "Total env impact." We can see all contractors choose the facility with the minimal cost for themselves. For example, contractor 1 chooses facility 1 among type 1. The facility selection principle is satisfied. Note that there exist two equally minimal choices for contractor 2, that is, facility 3 among type 2 and facility 3 among type 3. In this situation, contractor 2 could choose the facility that could reduce environmental impacts. This phenomenon indicates that the pricing scheme indeed adjusts the contractor's facility selection decision and reduces the environmental impact.

We proceed to examine the situation with the constraint of minimal charging target. The minimal charging target $\underline{X}$ is set as 100. The calculated CWDC fees are $x_1 = 39$ ($), $x_2 = 40$ ($), and $x_3 = 40$ ($), respectively. The facility selection results are the same as the results presented in Table 4. Therefore, the waste disposal payment for contractor 1, 2, 3 are 39 ($), 40 ($), and 40 ($), respectively. The total payment equals 119, which satisfies the minimal charging target. The optimal objective value still equals 186.

Note that an interesting phenomenon shown in Table 4 is that although the CWDC scheme could adjust a contractor's decision and reduce total environmental impact, the adjustment level is limited. The pricing scheme is based on the facility type, therefore, it cannot change the facility choice decision of facilities of the same type. For example, for contractor 1, the total environmental impact of facility 3 among type 2 is minimal among all candidates. However, since the pricing scheme x_i is the same for all facilities among type 1, the contractor would always choose facility 1 in type 2. Therefore, a minimal environmental impact facility cannot be chosen. This phenomenon demonstrates the necessity of proposing a more specific facility-based pricing scheme, that is, model [M4].

We keep the same parameter setting as [M2]. The pricing upper bound for each waste disposal facility and the minimal charging target are also set as $\bar{x} = 40$ and $\underline{X} = 100$,

TABLE 4 Computational results of the basic construction waste disposal charging (CWDC) scheme.

Construction site	Facility type	Facility	Transportation cost per ton ($)	Charge per ton ($)	Contractor's total cost ($)	Contractor's choice	Total env impact
1	1	1	3	0	3	1	43
		2	15	0	15	0	57
		3	19	0	19	0	39
	2	1	2	40	42	0	65
		2	18	40	58	0	40
		3	21	40	61	0	30
	3	1	29	40	69	0	46
		2	2	40	42	0	44
		3	13	40	53	0	72
2	2	1	26	40	66	0	32
		2	21	40	61	0	67
		3	4	40	**44**	0	70
	3	1	12	40	52	0	43
		2	7	40	47	0	83
		3	4	40	**44**	1	68
3	3	1	21	40	61	0	44
		2	3	40	43	1	75
		3	10	40	50	0	90

respectively. The solution results are presented in Table 5. In this table, we report (i) the optimal charge per ton, that is, x_{ij}, which is presented in the column "Charge per ton," (ii) the cost of choosing a facility, that is, $c_{ijk} + x_{ij}$, which is presented in the column "Contractor's total cost," (iii) contractors' choice decision, that is, z_{ijk}, is presented in the column "Contractor's choice." We can see that the facility-based CWDC scheme further changes contractors' facility choice decision and reduces the CW environmental impact. Specifically, the total environmental impact index, that is, objective value, is reduced from 186 to 161. By comparison, the total environmental impact index of the current charging scheme (shown in Table 2) is 210.

Contractors choose the minimal cost facility for themselves, which satisfies the facility selection principle. Due to the CWDC scheme being more specific, contractor 2 can change its selection decision to facility 3 among type 1, which reduces the environmental impact index by 25. The contractors' total payment equals 100, which satisfies the charging requirement. What is more, due to the adjustment of CWDC fee, there exist three equally minimal choices for contractor 2. In this situation, contractor 2 tends to choose the facility that could reduce environmental impact, that is, facility 3 among type 1. Note that there is no economic distinction between the three types of facilities. In other words, we obtain the critical point (or balance point). This phenomenon is consistent with Principle 1. Without the proposed CWDC, contractors will have no motivation to choose type 1 facilities. We can also make type 1 facilities the strictly minimal cost choice by numerical approach.

5.2 | Larger instances

In this section, we perform extensive randomly generated instances to verify the applicability of the proposed model. First, we study four groups of medium instances. Each group has different numbers of contractors. Table 6 shows these parameters in detail.

In each group, we generate five instances and, in each instance, transportation cost and environmental impact index are generated as follows: (i) the CW transportation cost per ton is between 5 and 300; (ii) the CW transportation environmental impact index per ton is between 10 and 500. The environmental impact indexes of disposing one ton CW are set to be 100, 200, and 400 for type 1, 2, and 3 facilities, respectively. The CWDC fees before optimization are set as 50, 100, 100 for type 1, 2, 3 facilities, as a benchmark for optimization models. The pricing upper bound $\bar{x}$ is set to be 300, which is three times larger than the current charging bound. The minimal charging target $\underline{X}$ is set to be 200. Other parameters are the same as the case in Section 5.1.

Table 7 reports the group ID, instance ID, total environmental impact index (TEI) without optimization, TEI of

TABLE 5 Computational results of the extended construction waste disposal charging (CWDC) scheme.

Construction site	Facility type	Facility	Transportation cost per ton ($)	Charge per ton ($)	Contractor's total cost ($)	Contractor's choice	Total env impact
1	1	1	3	31.3	34.3	1	43
		2	15	22.6	37.6	0	57
		3	19	40	59	0	39
	2	1	2	40	42	0	65
		2	18	19.6	37.6	0	40
		3	21	36.6	57.6	0	30
	3	1	29	28.6	57.6	0	46
		2	2	40	42	0	44
		3	13	36.6	49.6	0	72
2	2	1	26	40	66	0	32
		2	21	19.6	**40.6**	0	67
		3	4	36.6	**40.6**	0	70
	3	1	12	28.6	**40.6**	1	43
		2	7	40	47	0	83
		3	4	36.6	40.6	0	68
3	3	1	21	28.6	49.6	0	44
		2	3	40	43	1	75
		3	10	36.6	46.6	0	90

TABLE 6 Description of the four group instances.

Contractor types	Group 1	Group 2	Group 3	Group 4
Number of contractors that have entirely inert construction waste (CW)	5	10	15	20
Number of contractors that have more than 50% inert CW	5	10	15	20
Number of contractors that have less than 50% inert CW	2	3	5	8

the basic CWDC scheme (e.g., [M2]), TEI of the extended CWDC scheme (e.g., [M4]), the relative gap (RG) defined as $(Obj^{M1} - Obj^{M2})/Obj^{M2}$, and the standard deviation (SD). As shown in Table 7, the CWDC scheme generated by [M2] significantly reduces the environmental impact. It can be expected that [M2] can reduce an average of 17.77% of the TEI compared with the original pricing scheme. [M4] further significantly reduces the environmental impact. An average 15.84% reduction can be achieved compared with [M2]. We proceed to consider five large-scale instances in which the number of contractors that generate entirely inert CW, more than 50% inert CW, and less than 50% inert CW are set to be 50, 50, 10, respectively. The results are shown in Table 8. Both [M2] and [M4] perform well on large-scale instances. Compared with [M2], the extended model [M4] can further reduce an average of 8.72% environmental impact of disposing CW. This improvement is not negligible, considering the large amount of daily generated CW in the real world. A slight improvement would bring great environmental benefits.

Moreover, the SD of the gaps between the solution generated by [M2] and the solution generated by [M4] is large when the size of the instance (the number of contractors) is small. This tendency is not surprising, since the characteristics of the contractors are independent. The SD gradually decreases (not strictly due to the randomness) as the size of the instance grows. In other words, a stable performance improvement of [M2] and [M4] can be observed when the number of contractors is large.

5.3 | Case study

In this section, we investigate a real-world case in the context of Hong Kong with an area of 1113.76 km^2. A total of 16 CW disposal facilities are distributed in the Hong Kong Island, Kowloon, and outlying islands within Hong Kong waters (four facilities dispose 100% inert CW, two facilities dispose CW with more than 50% inert CW, and 10 facilities dispose CW any percentage of inert CW). The locations are obtained from the government's CWDC scheme webpage:

TABLE 7 Computational results of four group instances.

Group	Instance	Total environmental impact index (TEI)	TEI [M2]	TEI [M4]	Relative gap (RG)	SD
1	1	6536	5071	4423	14.65%	0.0864
	2	6161	5188	4574	13.42%	
	3	6218	4881	4016	21.54%	
	4	6321	5226	3796	37.67%	
	5	5551	5051	4130	22.30%	
2	1	11356	10057	8261	21.74%	0.0366
	2	11217	9808	8297	18.21%	
	3	12499	10707	9160	16.89%	
	4	11021	10338	9309	11.05%	
	5	12747	10023	8803	13.86%	
3	1	17490	15132	13670	10.69%	0.0195
	2	19415	16749	14692	14.00%	
	3	17614	15012	13755	9.14%	
	4	18233	14968	13228	13.15%	
	5	18113	14279	12524	14.01%	
4	1	22022	18001	16378	9.91%	0.0689
	2	22551	20838	16497	26.31%	
	3	21868	18645	17196	8.43%	
	4	21258	18603	17296	7.56%	
	5	22588	20148	17945	12.28%	

TABLE 8 Computational results of five large-scale instances.

Instance	Total environmental impact index (TEI)	TEI [M2]	TEI [M4]	Relative gap (RG)	SD
1	55421	48378	44222	9.40%	0.0254
2	52410	48629	44917	8.26%	
3	52888	45620	43710	4.37%	
4	55759	48271	43005	12.25%	
5	53734	48446	44313	9.33%	

https://www.epd.gov.hk/epd/misc/cdm/scheme.htm. The construction sites should be in built-up areas in practice. Therefore, we generate 120 construction sites in built-up areas, such as public/private residential, industrial land, and community facilities. Figure 2 shows the locations of CW disposal facilities and construction sites in Hong Kong region. The dots represent construction sites. Different colors represent different types of construction sites. The squares, triangles, pentagons represent type 1, 2, 3 CW disposal facilities, respectively. Given the locations, the travel distance between construction site k and CW disposal facility j can be easily derived from an online map application programming interface, for example, https://lbs.amap.com/. The CW quantities are generated according to the construction data for Hong Kong (Poon et al., 2004). The environmental impact of CW transportation and disposal are estimated through consultation with practitioners in construction industry.

Figure 3 shows the optimal solution of the basic CWDC model. Contractors sent their CW to the CW disposal facility to minimize their total cost. For example, contractor $k = 2$ sent its CW to facility $j = 9$. The government reduces concerned environmental impact by resetting CW disposal price. The value of TEI is able to decrease from 8502.27 to 7345.66 after solving [M2]. Then, we solved [M4] and found the value of TEI further decrease from 7345.66 to 7052.66. In other words, the value of TEI decreases from 8502.27 to 7052.66 after solving [M4], which also demonstrates the applicability of the proposed CWDC scheme in the real-world case.

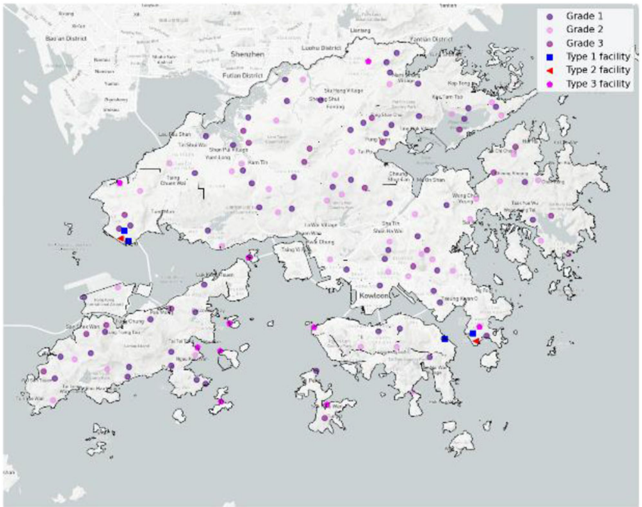

FIGURE 2 Layout of construction waste (CW) disposal facilities and construction sites.

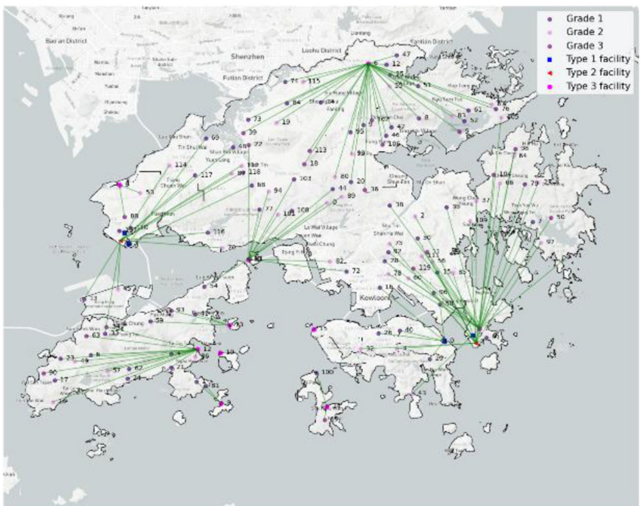

FIGURE 3 Optimal solution of the basic construction waste disposal charging (CWDC) model.

6 | CONCLUSIONS

To further enhance the effectiveness of the CWDC scheme, this study identified two intertwined issues faced in actual practice in Hong Kong and made the first attempt to integrate contractors' behavior characteristics and the impact of CW transportation into the design of the CWDC scheme. Specifically, the contractors' decision on the selection of CW disposal facility is modeled, which considers both the CWDC fee and the transportation cost. The EPD aims to let more contractors transport their generated CW to appropriate CW disposal facilities and then decrease the total environmental impact of CW disposal and transportation based on better understanding of the behavior characteristics of contractors. This methodology is expected to enhance the effectiveness of the CWDC scheme in practice aiming at decreasing environmental impacts. From a theoretical perspective, this work established a bilevel framework to design the pricing of CWDC schemes, which models the contractors' behavior and the transportation process from construction sites to waste disposal facilities. The formulated models are then transformed into single-level models and further linearized. Extensive randomly generated instances are investigated to further verify the effectiveness of our CWDC methodology.

Currently, most studies focus on the performance evaluation of the CWDC scheme while few investigate the CWDC scheme design. Yuan and Wang (2014) and Mak et al. (2019) are only two related studies in the field of CWDC scheme design. However, both of them utilize simulation-based approaches. In our research, we studied the CWDC scheme design through the operation research approach. The CW disposal is a complex system that involves multiple stakeholders and associated facilities, such as the government and its executive arms, contractors, CW disposal facilities, road network. Therefore, it is necessary to analytically formulate the backbone operating framework.

CW management is a common challenge around the world. CWCD scheme has been implemented in many countries and areas, such as European Union, Malaysia, Hong Kong, and China (Calvo et al., 2014; Duan et al., 2015). Our proposed CWDC schemes have a wide range of applicability and can be applied in various CW disposal scenarios.

This study uses operation research models for the optimal design of CWDC scheme. Given the behavior diversity of contractors, more decision behaviors can be considered in future research. The influence of CWDC on CW reduction and recycling can also be investigated in the future and is expected to contribute to more effective CWDC scheme and management policies. In addition, when the proposed CWDC scheme comes into practice, the government should concern the contractors' acceptability. Despite its benefit to urban environment, the contractors' acceptance may prevent its implementation. Meanwhile, how to deal with capacity constraint of CW disposal facility and how to appropriately collect and calibrate the parameters in the model are also challenges that should be taken into account.

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