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Optimization of municipal solid waste management using a coordinated framework

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ABSTRACT

Municipal solid waste (MSW) management is an important but complex logistical problem. The deployment of MSW management systems is hindered by the ever-growing generation of waste and the often insufficient infrastructure to manage, process, and dispose of waste. This paper presents a coordinated framework for complex MSW management systems. The framework accommodates multiple key stakeholders in MSW systems, such as suppliers of waste, consumers of waste and derived products, and providers of transportation and processing services. Here, the stakeholders submit bids to a coordinator that solves an optimization problem to determine allocations and clearing prices that maximize the collective profit for all stakeholders and that balance supply and demand for waste and products. Furthermore, the clearing process guarantees that the individual profits are non-negative (no stakeholder loses money). Notably, the framework operates as a competitive market that accelerates transactions between stakeholders and that handles complex logistical constraints that would be difficult to handle in peer-to-peer transactions. The framework also facilitates the integration of policy incentives and the monetization of environmental impacts. In this regard, we evaluate a tax applied to open dump disposal. To illustrate the applicability, an MSW system in Mexico was analyzed as a case study. Results reveal that taxation can be used to incentivize the provision of services for all stakeholders. Specifically, we found that an appropriate tax can completely avoid disposal in open dumps. A tax of 5.1 USD/tonne was identified as the minimum penalization that avoids diverting waste to open dumps.

1. Introduction

Waste management is a growing and overwhelming concern around the world; this is particularly true in developing countries, where waste generation is sharply increasing and there is no sufficient collection and processing infrastructure (Yousefloo and Babazadeh, 2020). The lack of these types of systems has led to significant social and environmental issues that increase year by year with the generation of waste. According to the World Bank, the annual solid waste generation globally was 1.3 billion tons in 2012 and is expected to grow to 2.2 billion tons by 2025 (Hoornweg and Bhada-Tata, 2012). In the USA, the waste generation per day is approximately 0.64 MT, followed by Germany with 0.14 MT, Mexico with 0.13 MT, and Japan with 0.10 MT (Das et al., 2019). Landfill space and the collection and processing infrastructure are becoming increasingly constrained in large urban centers and might require the use of uncontrolled (open dump) sites for disposal (Ojeda-Benitez and Beraud-Lozano, 2003). The use of open dump systems is a common practice in developing countries such as Mexico. The Mexican environmental protection agency (SEMARNAT) reported in 2012 that, of all waste generated in the country, 72% was disposed of at sanitary landfills and regulated sites, 23% was disposed at open dumps, and only 5% was recycled (Semarnat, 2012).

Unfortunately, the environmental, social, and safety impacts of open dump systems have not received as much attention from policy-makers and academics (Medina, 2010). These systems do not provide technologies of controlled landfills, such as leachate treatment, geological protection, and gas treatment (Ojeda-Benitez and Beraud-Lozano, 2003). As a result, methane, produced by the decomposition of organic materials, can leak to the environment and can trigger fires. Also, strong leachates can pollute surface and groundwater. Food leftovers can attract wildlife which

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Nomenclature

Parameters

c_d^*	Maximum capacities for the consumers
f_m^*	Maximum capacities for the technology providers
g_s^*	Maximum capacities for the suppliers
q_k^*	Maximum capacities for the transportation providers
α_d	Bidding information for the consumers
β_s	Bidding information for the suppliers
δ_m	Bidding information for the technology providers
γ_k	Bidding information for the transportation providers
$\varsigma_{m,p}$	Conversion factor for each technology and product

Variables

c_d	Allocations for the consumers
f_m	Allocations for the technology providers
g_s	Allocations for the suppliers
q_k	Allocations for the transportation providers
π_d	Clearing prices for the consumers
π_s	Clearing prices for the suppliers
π_k	Clearing prices for the transportation providers
π_m	Clearing prices for the technology providers
ϕ_d^D	Profits for the consumers
ϕ_s^S	Profits for the suppliers
ϕ_k^K	Profits for the transportation providers

can transmit diseases to humans. In addition to this, biodegradation of organic waste can take many years, limiting the future use of the land used by the open system (Medina, 2010).

Recently, the collection, storage, and recycling of solid wastes in Mexico have started to be incentivized. Recycling has increased from 2.3% in 2000 to 5% in 2012 (Botello-Álvarez et al., 2018). However, this percentage remains very small comparing to waste recycled worldwide (approximately 19%) (Gutberlet, 2015). Several policies and financing strategies are currently being investigated to accelerate the deployment of more advanced waste management systems around the world. A hypothetical scenario reported in Korea considers a tax collection framework that incentivizes the deployment of recycling facilities. This analysis indicates that people are willing to bear the cost of discarding recyclable waste (Ko et al., 2020). Similarly, studies in Serbia have revealed that residents are in general willing to pay for a pharmaceutical disposal program (Paut Kusturica et al., 2020). These studies also argue that there is a need to establish policy regulations for waste-dumping and the allocation of financial resources for waste collection. On the other hand, a hypothetical landfill tax scenario in Israel shows that recycling does not improve greatly with the inclusion of externality costs (Lavee, 2007). Furthermore, a management cycle for waste, including the participation of infrastructure managers, workers, and households, was recently proposed by Jiang et al. (2020). Here, the waste-dumping behavior and empirical decisions of each part are considered to guide policy regulations.

Financial sustainability is a major issue in the design of solid waste management (SWM) systems. In this regard, a cost-revenue analysis for an SWM system in Bahir Dar revealed that the cost-structure of waste services must be improved to enable sustainability (Lohri et al., 2014). This study proposed some alternatives to achieve this: improving fee collection, increasing the value chain by sales of recyclables and derived products, including financing mechanisms (such as polluter payments and cross-subsidies), and improving overall efficiencies. Furthermore, models for waste recycling between enterprises through industrial symbiosis have been reported. Here, different supply–demand relationships were considered to find optimal waste pricing decisions. The results show that industries tend to cooperate when the marginal cost of recycling is lower than the cost of the raw materials (He et al., 2020). An important observation is that this symbiosis is effectively a coordinated market framework. Recently, a general coordinated market framework for organic waste that facilitates transactions between multiple stakeholders (suppliers of waste, consumers of waste and derived products, transportation providers, and processing facilities) was proposed by Sampat et al. (2019). This approach seeks to find allocations for all stakeholders and clearing prices for waste and derived products that maximize the collective profit of all stakeholders. Notably, it is shown that the management framework is equivalent to a competitive market and inherits key economic properties for such markets, such as revenue adequacy (payments from consumers cover costs associated with waste supply, collection, and processing). Moreover, this framework can help monetize environmental impacts to foster investment and development efforts. The authors argue that the framework can be used to predict the impact of distinct regulations or incentives and is scalable since it provides open access that promotes transactions between large numbers of stakeholders.

Other optimization models have been previously proposed for MSW management systems. A supply chain optimization model for an MSW system that considers economic, social, and environmental factors was proposed by Mohammadi et al. (2019). Furthermore, a mathematical optimization approach that includes waste reduction processes and landfilling has been reported by Garibay-Rodriguez et al. (2018). The results show that the deployment of a landfill gas-to-energy system and a material recycling facility can improve the overall economics of the MSW system (a step towards achieving financial sustainability). Regarding the economic efficiency of recycling, an approach that reveals its viability has been reported by Lavee (2007). The presented results show that 51% of the municipalities of Israel can benefit from adopting recycling. The beneficiaries were mostly large municipalities. An important issue here is the uncertainty related to the price of recycled materials, which may discourage municipalities and make them prefer landfill disposal (Lavee et al., 2004). To overcome this problem, options to stabilize prices and ensure long-term contracts with recycling plants have been proposed. This approach avoids unnecessary investments given by the repeated change of disposal methods (Lavee et al., 2009). Moreover, a multi-objective model including the minimization of costs and risk objectives for an MSW supply chain network has been developed by Yousefloo and Babazadeh (2020). The risk function captures the population affected by waste treatment centers and emissions that result from waste processing. This work involves a real case study in Iran. Another multi-objective model to allocate waste to treatment technologies was proposed by Minoglou and Komilis (2013). Here, operational and transportation costs are considered, as well as different processing options (incineration, compost, anaerobic digestion, and landfilling). The minimization of costs and emissions are used as objective functions. Distinct methods to capture the collection and transportation of waste were reported by Paul et al. (2018). In their linear programming model, the optimal allocation of waste to different processing technologies was evaluated. Mixed-integer programming models have also been proposed to find the optimal number of collection trucks in an MSW system in Hong Kong (Lee et al., 2016). A mathematical model to perform optimal planning that maximizes the profit has been reported by Santibañez-Aguilar et al. (2013). Here, the maximization of recycled waste is considered. Optimal technologies along with their geographical location, as well as the distribution of waste and products from and to different cities, are selected through the model. The results also identify tradeoffs between economic and environmental objectives. A common issue with these studies is that they take a "central" view of the problem in which the entire MSW system is operated by a single stakeholder. As a result, these models do not provide insights into how different components of the system should be remunerated. Furthermore, previous approaches have not focused on every stakeholder that participates in the MSW system and on their profits. Specifically, a framework where the total welfare or collective profit of all stakeholders is considered along with the profits and allocations of each stakeholder has not been reported. These considerations are important, since in a real application of MSW management all participants matter. Moreover, balancing supply and demand through a coordinated framework avoids economic losses, because the revenue collected from the consumers covers the payments of suppliers and providers.

In this work, we present an optimization formulation for MSW management systems within a coordinated market framework. The proposed model includes the optimal planning for MSW considering different alternatives for the disposal of waste: sanitary landfills, open dumps, and reuse. Specifically, the mathematical model involves several stakeholders: urban centers that produce waste, sanitary landfills and open dump systems, processing technologies for different types of waste, and financial consumers of derived products. From a coordinated market perspective, suppliers and consumers (demand) of waste and products, as well as providers (both transportation and technology), can be identified in the MSW system. Additional details about the coordinated management are explained in **chapter 2**. Moreover, in **chapter 4**, we show how to use the coordinated framework to identify suitable tax structures for the disposal of waste in open dumps. The results reveal that taxation can effectively incentivize the provision of services by all stakeholders. Specifically, we found that an appropriate tax can avoid open dumps disposal completely. Moreover, the optimal allocation that provides positive profits for each stakeholder was identified through the coordinated framework. To illustrate the applicability of this approach, an MSW system in Mexico was analyzed as a case study. However, the formulation is general and can be applied to any MSW system. In this regard, our objective is to provide a coordinated management perspective for MSW systems by including taxation to avoid negative environmental impacts. Particularly, we focused on the impact of open dump systems, but the approach can be extended to include other environmental issues.

The presented approach is structured as follows: **chapter 2** describes the elements of the MSW system and additional considerations for the coordinated management. **Chapter 3** describes the mathematical model formulation of the proposed system. **Chapter 4** refers to the applicability of the formulation through a case study in the central-west region of Mexico.

2. Coordinated MSW management system

The proposed system comprises different suppliers, consumers, and providers of transportation and processing (transformation) services involved in MSW management. As mentioned in **chapter 1**, these stakeholders can be identified from a coordinated market perspective. Furthermore, each of these stakeholders manages distinct waste or products at a particular geographical location. These considerations can be visualized in the superstructure shown in Fig. 1. Here, we can see that several urban centers (geographical locations) are considered, each of them involves a specific generation rate of different types of waste (plastic, metal, organic, glass, and non-recyclables). Moreover, these types can be classified in subtypes (such as clear, green, and brown glass). Note that the urban centers act as suppliers of waste for the sanitary landfills (which act as consumers) and the processing facilities. Urban centers also act as consumers that purchase products from the processing facilities. It is considered that the waste that is not allocated to consumers is sent to open dumps. This is a common practice in developing countries, despite the environmental, social, and safety impacts (Medina, 2010). In a typical situation, it is assumed that this can be done at no cost (or at a small cost). This cost is economic and does not involve the environmental cost, which can be greatly expensive. Therefore, to prevent open dump disposal, we include a tax for the waste disposed at such systems.

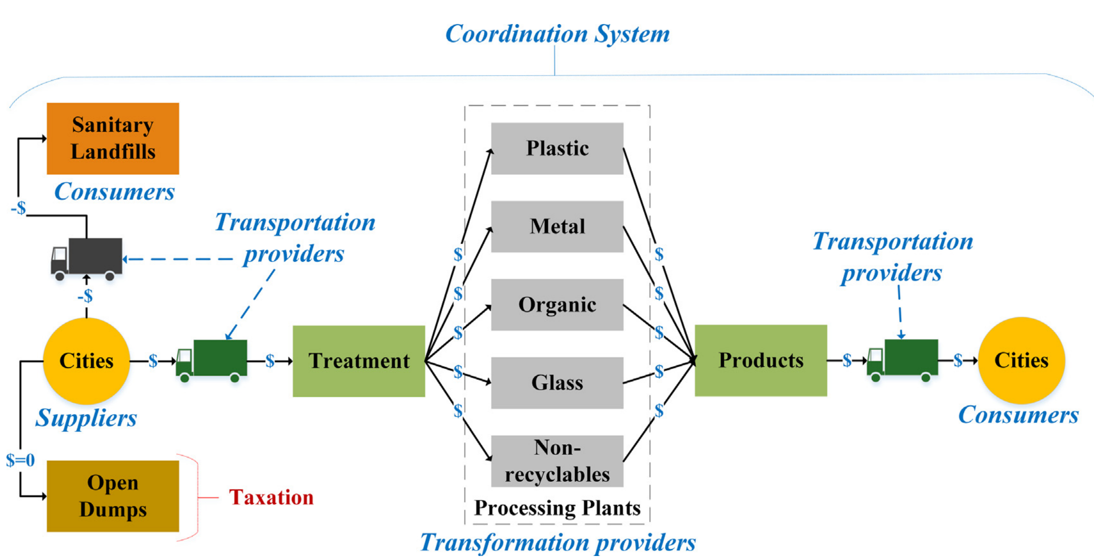

Fig. 1. Proposed superstructure for the coordinated MSW system.

This tax can be interpreted as a service that the environment provides to society (the environment absorbs the impacts of the waste but at a cost). The MSW system also includes sanitary landfills, open dumps, and processing facilities in each urban center. The processing providers offer different types of treatment and technologies for each waste type. The transportation providers can move waste to sanitary landfills, to processing facilities, and final consumers. The stakeholders are categorized by the type of waste they handle (plastic, metal, organic, glass, and non-recyclables).

Some additional considerations of the coordination system are explained in the following. First of all, suppliers, consumers, and service providers submit bids into the coordinated system. Then, a coordinator, known as an independent system operator (ISO), uses bid information to determine allocations and prices to clear the market. All stakeholders offer positive bids, except for landfills, which offer negative bids. On the one hand, the negative bid of landfill suppliers is a payment that they are willing to give to the market to take away their waste. On the other hand, the negative bid of a landfill demand indicates that the landfill will take the waste only if it is paid for doing so (such as a disposal cost or tipping fee). Given this information, the coordinator clears the market by solving an optimization problem that maximizes the total welfare (collective profit of all the stakeholders). The optimization formulation solved by the ISO includes the sales and costs of the market stakeholders. The cleared stakeholders are paid based on their product allocations and associated clearing prices. Transportation providers are paid based on differences in clearing prices at the source and destination locations, while the processing providers are paid based on the clearing prices or their input and output products. When a stakeholder is not cleared (it is allocated no product), this means that this player does not participate in the market. All of these considerations are used for the formulation of the model, as shown in **chapter 3**. Furthermore, two scenarios are analyzed: I) the base case (without taxation) and II) a case with a tax for the amount of waste that ends up in open dumps. This tax represents the service that the environment provides and may prevent open dump disposal. The solutions of the ISO problem satisfy a set of fundamental economic properties of a competitive market (Sampat et al., 2019). Specifically, the clearing process guarantees that no cleared player loses money and that there is revenue adequacy (total payments collected equal total payments made).

3. Formulation of the coordination problem

The proposed model is deterministic, and it is based on the superstructure shown in Fig. 1 as well as on the considerations mentioned above. In the following, the equations of the model for the MSW management system using the coordinated framework are presented. Additionally, complementary equations, based on the formulation proposed by Santibañez-Aguilar et al. (2013), are shown in the **supplementary material section**. As stated in **chapter 2**, we consider a framework that is composed of a set of geographical locations N, products P, consumers D, suppliers S, transportation providers K, and transformation (technology) providers M.

In the MSW system addressed here, previous elements are identified as (i) the geographical locations refer to where waste is generated, where the products are consumed, and where sanitary landfills and processing plants are placed; (ii) the products represent the different types of waste and derived products obtained from the processing facilities; (iii) the suppliers represent the urban centers that generate waste, while the consumers are the urban centers that demand waste (sanitary landfills) and useful products (from processing plants); (iv) the transportation providers refer to the service of transport to move the waste from urban centers to landfills and plants, and from plants to urban centers; and (v) the processing providers refer to the different technologies to treat waste.

The bidding information $(\alpha_d, \beta_s, \gamma_k, \delta_m)$ as well as the maximum capacities $(c_d^*, g_s^*, q_k^*, f_m^*)$ for the demand (c_d), supply (g_s), transportation (q_k), and transformation (f_m) are given (as previously indicated in **chapter 2**). The objective function in Eq. (1) maximizes the total welfare, which refers to the difference between the demand served and the costs of supply, transportation, and transformation. The solution to the problem includes finding the corresponding allocations (c_d, g_s, q_k, f_m) and prices that clear the market and maximize the collective profit of all the stakeholders (total welfare). These allocations satisfy the physical conservation laws in Eq. (2), and capacity constraints in Eqs. (3)–(6). The dual variables $(\pi_{n,p}), (n,p) \in N \times P$ act as market clearing prices by setting values for products at different locations. Here, $\varsigma_{m,p}$ refers to the conversion factor for each technology and product.

$$\max \sum_{d \in D} \alpha_d c_d - \sum_{s \in S} \beta_s g_s - \sum_{k \in K} \gamma_k q_k - \sum_{m \in M} \delta_m f_m \tag{1}$$

$$\text{s.t.} \sum_{s \in S_{n,p}} g_s - \sum_{d \in D_{n,p}} c_d + \sum_{k \in K_{n,p}^{in}} q_k - \sum_{k \in K_{n,p}^{out}} q_k + \sum_{m \in M_n} \varsigma_{m,p} f_m = 0, (n,p) \in N \times P, (\pi_{n,p}) \tag{2}$$

$$0 \le c_d \le c_d^*, d \in D \tag{3}$$

$$0 \le g_s \le g_s^*, s \in S \tag{4}$$

$$0 \le q_k \le q_k^*, k \in K \tag{5}$$

$$0 \le f_m \le f_m^*, m \in M \tag{6}$$

The computed allocations and prices from the optimization problem are used to remunerate providers and to charge consumers. This leads to revenue adequacy, which means that the revenue collected is equal to the payments made. We use the notation $(\pi_d, \pi_s, \pi_k, \pi_m)$ to refer to the locational marginal prices (clearing prices) at the corresponding locations of each stakeholder. For consumers, $\alpha_d c_d$ refers to the monetary value of the allocated demand, while $\pi_d c_d$ is the payment made to the market. Therefore, the profit for consumers (ϕ_d^D) is the difference between these values, as shown in Eq. (7). For suppliers, $\pi_s g_s$ represents their revenue and $\beta_s g_s$ refers to their operating cost. The profit for suppliers is thus the difference between these values (Eq. (8)). The profit for transportation providers is estimated by Eq. (9). Here, π_k are the transportation prices that are estimated by the difference between the prices of the destination nodes and the prices of the origin nodes. The quantity $\pi_k q_k$ is the payment made to the transportation providers and $\gamma_k q_k$ is their operating cost. The transformation prices π_m are calculated as a weighted sum of marginal prices (weighted by conversion factors) for the products involved in the processing step. Note that the conversion factors are given parameters. The profit of these providers is computed as shown in Eq. (10), $\pi_m f_m$ represents their revenue while $\delta_m f_m$ is their operating cost.

$$\phi_d^D = (\alpha_d - \pi_d) c_d, d \in D \tag{7}$$

$$\phi_s^S = (\pi_s - \beta_s) g_s, s \in S \tag{8}$$

$$\phi_k^K = (\pi_k - \gamma_k) q_k, k \in K \tag{9}$$

$$\phi_m^M = (\pi_m - \delta_m) f_m, m \in M \tag{10}$$

The clearing process guarantees that these profits are nonnegative (no stakeholder loses money), this is a key benefit of the coordinated market.

4. Results and discussion

We apply our framework to a case study that seeks to analyze how an MSW system would operate in the central-west region of Mexico. As shown in Fig. 2, five urban centers (Morelia, Celaya, Apatzingan, Lazaro Cardenas, and Leon) act as suppliers and consumers into the coordination system. Here, the different participants are identified as follows: *S* for suppliers, *D* for consumers, *K* for transportation providers, and *M* for processing providers. The numbers *1–5* denote where each stakeholder is situated. For instance, the technology provider *M1* is situated in the city of Morelia. Note that each processing provider has equal technologies locally available to treat each type of waste (plastic, metal, organic, glass, and non-recyclables). The different types of plastic are denoted by *R1*, *R2*, *R3*, *R4*, and *R5*. The different types of glass are denoted by *G1*, *G2*, and *G3*. Representative parameters of this application, such as the generation rate of waste at each city, are shown in the **supplementary material section**. The complete information of the case study, as well as the corresponding parameters, have been previously reported and can be found in Santibañez-Aguilar et al. (2013). Note that Fig. 2 is just a schematic representation of the case study to facilitate the visualization of all the participants and the possibilities of the system.

Associated with each of the MSW system participants there is a specific flow, product type, capacity, location, and bidding cost. For all types of waste, the same geographical locations (nodes) are considered, along with two possible pathways: sending the waste to a processing facility for treatment and sending the waste to a sanitary landfill. We also include the possibility of sending waste to open dumps. To account for this environmental impact, two scenarios are analyzed: I) base case in which we ignore the impact of dumps and II) a tax is applied to any waste amount disposed of at open dumps. After solving the problem, we find that the total welfare (collective profit) of the system is 871,744 USD and 784,061 USD for Scenarios I and II, respectively. As expected, accounting for the environmental impact incurs a penalty in the total welfare. Note that previous approaches have included taxation schemes, but to foster recycling. For instance, a tax applied to landfill disposal to increase the level of recycling has been reported by Lavee (2007). Furthermore, a tax collection scenario to install a recycling facility was evaluated by Ko et al. (2020). However, we focus on the taxation for open dump disposal to monetize this environmental impact. Our approach also considers processing facilities to treat waste and sanitary landfill disposal, but without applying direct taxation to these activities.

We use a tax of 5.1 USD/tonne; this value was identified as the minimum penalization that avoids diverting waste to open dumps. To obtain this value, we first used a tax equal to 12.35 USD/tonne (which corresponds to the cost of sending waste to the landfill). The results with this tax are shown in the **supplementary material section**. Then, the obtained lowest prices (marginal values) for the landfill supply of all types of waste were identified and evaluated as tax values. Distinct values from these prices were evaluated until the reported minimum tax (5.1 USD/tonne) was found. Comparing the allocations (profits) in the following results to those obtained in the **supplementary material section** with a tax equal to 12.35 USD/tonne, we can see that the minimum tax yields similar profit levels for all stakeholders. These results illustrate how our methodology can be used to systematically identify policies that incentivize different stakeholders in MSW systems.

The impact of the variability of the distinct prices involved in MSW systems has been previously addressed. For instance, the prices of waste recycling in an industrial park were analyzed by He et al. (2020). Besides, Mohammadi et al. (2019) found that the profit of an MSW system, involving the efficient use of waste, is affected by changes in electricity prices. Similarly, Lavee et al. (2009) reported that the uncertainty in recycling prices may make decision-makers prefer landfill disposal. On the other hand, our approach provides the clearing prices for all the involved stakeholders in the MSW system, including suppliers, consumers, and providers (of transportation and transformation). We observe that, depending on the scenario (with or without taxation for open dump disposal), the prices vary. Nevertheless, the prices related to the transformation providers do not change with the taxation since the tax do not have an impact on the recycled waste. The profits for each participant are estimated as well. Note that all the profits are non-negative. This occurs because participants do not lose money within a coordinated system.

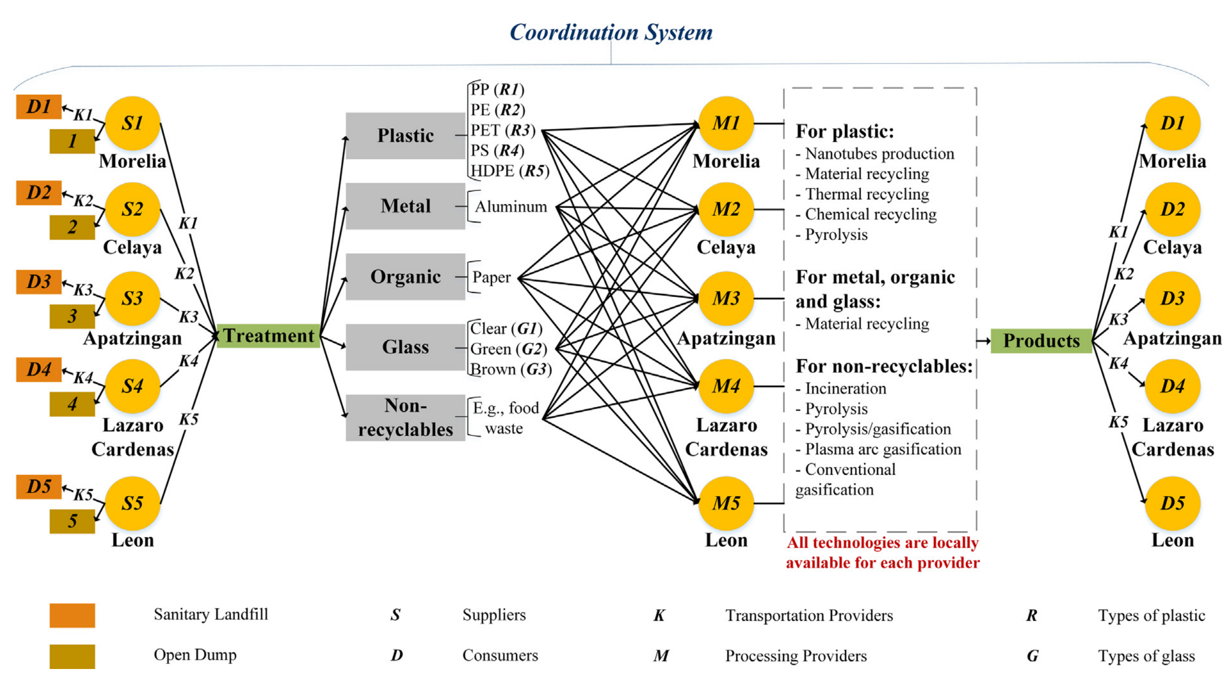

Fig. 2. Representation of the case study addressed for the MSW system.

4.1. Analysis for plastic waste

We first analyze the solutions for the evaluated suppliers (*S1-S5*), consumers (*D1-D5*), and transportation providers (*K1-K5*) of plastic. No transformation providers participate in the optimal solution for this type of waste. Thus, supply, demand, and transport refer to the plastic sent to the landfill. We can see that, for both scenarios, the supply and demand offer negative bid costs (see Table 1). These costs are equal for all types of plastic. The landfill supply with a negative bid is a payment that the suppliers are willing to pay the market to take away the waste. On the other hand, it was reported that disposal facilities can act as consumers (Sampat et al., 2019). Specifically, the landfill demand with a negative bid indicates that the landfill will take the waste only if it is paid for doing so (such as a disposal cost or a penalty cost). This behavior is included in the model because such incentives (suppliers are willing to pay) and penalties (disposal cost) are common in this type of market to promote appropriate waste management. Such as in (Paut Kusturica et al., 2020), where it was reported that residents are willing to pay for a pharmaceutical disposal program. Besides, Ko et al. (2020) found that people agree with a tax to be able to discard their recyclable waste. We can see that all the obtained clearing prices for the landfill supply (see Table 1) are such that the profit is non-negative for all players (no player loses money in the MSW system). This is a key property of coordinated markets (Sampat et al., 2019). In Scenario I, there is no plastic sent to the sanitary landfill and, thus, the profit is zero. The landfill suppliers do not participate in this scenario since all the waste is disposed of at open dumps. Contrary to Scenario II, where all the waste is disposed of at sanitary landfills due to the involved tax. On the one hand, the prices only vary depending on the stakeholder and not on the type of plastic; on the other hand, the profit varies by type of plastic due to the distinct flows of each material sent to the sanitary landfill (see Fig. 3).

Table 1 also shows the clearing prices for the landfill demand. Here, we can see that in Scenario I, all the clearing prices are higher than the bids; and, thus, the consumers are not allocated any product (they do not participate in the market). Therefore, all waste is allocated to open dump systems. We also observe that in Scenario II (with taxation), the obtained prices are such that all profits are non-negative and all waste is sent to sanitary landfills. This illustrates how, regardless of the tax used, participants do not lose money in a coordinated MSW system. Regarding the transportation providers of plastic entering the landfill, their prices are shown in Table 1 as well. Here, the obtained prices for Scenario I are lower than the bids, while for Scenario II all the clearing prices are greater. Therefore, only the prices from Scenario II allow finding positive profits, since they satisfy the constraints required for the transportation providers to have non-negative profits. As a consequence, the waste is transported to sanitary landfills in this scenario. Note that for the transportation providers' profits, we only consider the operational costs and not the optimal number of collection trucks as in Lee et al. (2016). Alternatively, our approach includes the optimal number of transportation providers that participate according to the clearing process. Within their operational costs, the expenses related to the needed trucks are included. The profits are categorized in Fig. 3 by type of plastic. Here, we observe some interesting trends; specifically, stakeholders 1 and 5 always make the largest profits followed by stakeholders 2 and 4; while stakeholder 3 makes the smallest profit. Regarding the types of plastic, *R1* and *R2* (corresponding to PP and PE) represent most of the total profit. Note that landfill suppliers attain the highest profits. Overall, we can see that the taxation scenario in the coordinated system avoids diverting waste to open dumps and simultaneously allows landfill providers to attain profits.

4.2. Analysis for metal waste

The following results refer to the solutions for metal waste. Table 2 and Fig. 4 present the information for the different suppliers (*S1-S5*), consumers (*D1-D5*), transportation providers (*K1-K5*), and technology providers (*M1-M5*). We only evaluate one type of metal (aluminum). For the landfill supply (see Table 2), we can see that all the prices are greater than the bids and, thus, the profits are all non-negative. Positive profits are only achieved in Scenario II (see Fig. 4). This occurs because the involved taxation prevents open dump disposal by making landfill suppliers participate. Consequently, the waste is disposed of at sanitary landfills. Contrary to Scenario I, where metal waste is sent to open dumps since the prices are not lower than the bids for the landfill demand. Therefore, these consumers are not cleared (there is lacking demand for waste) according to the requirements for the consumers to have non-negative profits. On the other hand, in Scenario II, the clearing prices are equal to the bids, so these consumers participate in the market (there is a landfill demand for waste), but their profit is zero. The optimal solution of metal waste includes transformation providers to process the waste in a processing facility for sale. Regarding the processing supply, we can see that all the clearing prices are greater than the bids and equal for both scenarios. Thus, we have positive and equal profits for both scenarios (see Fig. 4). For the processing plant demand, we observe that in both scenarios, only the prices of the consumer *D1* are lower than the bids. Therefore, *D1* attains a profit greater than zero. Such as in He et al. (2020), where it was reported that industries tend to cooperate when the marginal cost of recycling is lower than the cost of raw materials. Note that the other consumers (*D2-D5*) could be cleared obtaining a profit equal to zero, however, only *D4* participates in the market. As expected, the taxation scheme does not impact on the processing plant supply and demand, since the tax is applied only to the waste at open dump systems. The results for the transportation providers of the metal entering the landfill and processing plant, and of the products leaving the processing

Table 1
Bids and clearing prices for landfill supply, landfill demand, and transportation providers for plastic waste.

	Bids (USD/tonne)	Prices (USD/tonne)				
Landfill supply	***S1-S5***	***S1***	***S2***	***S3***	***S4***	***S5***
Scenario I	−12.35	0	0	0	0	0
Scenario II (with tax)	−12.35	−4.27	−4.26	−4.28	−4.29	−5.1
Landfill demand	***D1-D5***	***D1***	***D2***	***D3***	***D4***	***D5***
Scenario I	−12.35	−12.29	−12.31	−12.28	−12.28	−12.26
Scenario II (with tax)	−12.35	−16.57	−16.57	−16.57	−16.57	−17.36
Transportation providers (entering landfill)	***K1-K5***	***K1***	***K2***	***K3***	***K4***	***K5***
Scenario I	0.0165	−12.29	−12.31	−12.28	−12.28	−12.26
Scenario II (with tax)	0.0165	5.64	5.64	5.64	5.64	4.84

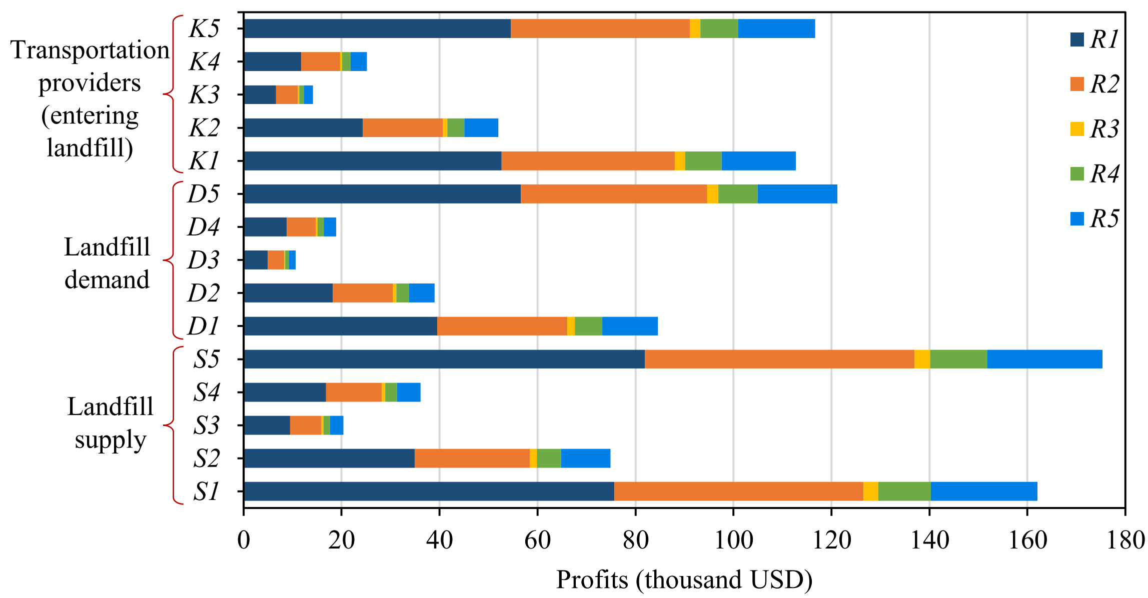

Fig. 3. Profits for landfill supply, landfill demand and transportation providers by types of plastic in Scenario II.

Table 2
Bids and clearing prices for supply, demand, transportation and technology providers for metal waste.

	Bids (USD/tonne)	Prices (USD/tonne)				
Landfill supply	***S1-S5***	***S1***	***S2***	***S3***	***S4***	***S5***
Scenario I	−12.35	0	0	0	0	0
Scenario II (with tax)	−12.35	−0.14	−0.11	−0.16	−0.17	−0.21
Landfill demand	***D1-D5***	***D1***	***D2***	***D3***	***D4***	***D5***
Scenario I	−12.35	−12.24	−12.19	−12.18	−12.14	−12.21
Scenario II (with tax)	−12.35	−12.35	−12.35	−12.35	−12.35	−12.35
Plant supply	***S1-S5***	***S1***	***S2***	***S3***	***S4***	***S5***
Scenario I	223.5	1204.2	1198.4	1196.6	1198.5	1196
Scenario II (with tax)	223.5	1204.2	1198.4	1196.6	1198.5	1196
Plant demand	***D1-D5***	***D1***	***D2***	***D3***	***D4***	***D5***
Scenario I	1300	1290	1300	1300	1300	1300
Scenario II (with tax)	1300	1290	1300	1300	1300	1300
Transportation providers (entering landfill)	***K1-K5***	***K1***	***K2***	***K3***	***K4***	***K5***
Scenario I	0.04	−12.21	−12.24	−12.19	−12.18	−12.14
Scenario II (with tax)	0.04	−11.56	−11.56	−11.56	−11.56	−11.56
Transportation providers (entering plant / leaving plant)	***K1-K5***	***K1***	***K2***	***K3***	***K4***	***K5***
Scenario I	0.04	90.1	101.64	103.44	101.52	104
Scenario II (with tax)	0.04	90.1	101.64	103.44	101.52	104
Technology providers	***M1-M5***	***M1***	***M2***	***M3***	***M4***	***M5***
Scenario I	90	1294.2	1300	1300	1300	1300
Scenario II (with tax)	90	1294.2	1300	1300	1300	1300

plant are also presented in Table 2. For the transportation providers of the metal entering the processing plant, we observe that all the prices are greater than the bids, which allows the profits to be positive. These profits are equal for both scenarios since the clearing prices are equal as well. We observe that the prices for the transportation providers of the metal leaving the processing plant are equal to those obtained for the transportation providers of the metal entering the processing plant. However, only the providers *K1* and *K4* are cleared here. Again, the profits are equal for both scenarios. The total profits for the transportation providers of each scenario are presented in Fig. 4. These total profits are the sum of the profits of the providers of the metal entering the sanitary landfill and processing plant, and of the providers of the products leaving the processing plant. We can see that the profits are positive for both scenarios, but in Scenario I the profits are greater since no metal is sent to the landfill (instead, open dump disposal occurs). For the technology providers, we observe that all the clearing prices are greater than the bids, but only the provider *M1* participates in the market for both scenarios (the tax does not impact on these stakeholders). Here, material recycling is used to process the metal and the profit for provider *M1* is 1,070,035 USD. Note that this provider attains the highest level of profit followed by the processing plant suppliers, the transportation providers, the landfill suppliers, and the processing plant demand. Furthermore, we can see how including taxes fosters the sanitary landfill disposal, despite only landfill suppliers (and not landfill

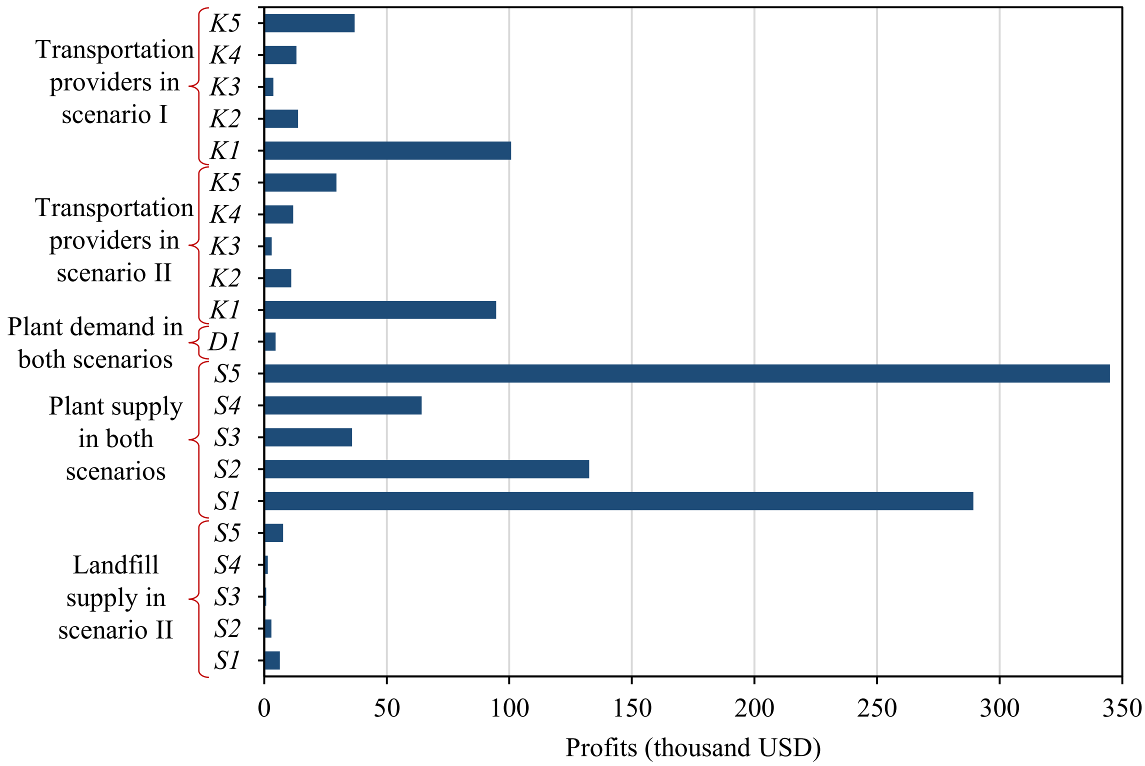

Fig. 4. Profits for supply, demand and transportation providers of metal for Scenarios I and II.

consumers) attain profits greater than zero. This occurs since even with the profit of landfill consumers being zero, they do not lose money and, thus, participate in the market.

4.3. Analysis for glass waste

The solutions for the different types of glass (*G1*, *G2*, and *G3*) are presented in Table 3 and Fig. 5**.** Note that no processing players participate here (as in the case of plastic). The results reveal that taxation incentivizes the provision of landfill services and avoids open dump systems for every type of glass. Specifically, for landfill supply, all the prices are greater than the bids; however, positive profits are attained only for Scenario II because in Scenario I there is no glass sent to the sanitary landfill. Therefore, all waste is diverted to open dumps. For the landfill demand, every consumer in Scenario II has positive profits as well. Note that the taxation scenario allows the generation of landfill demand to prevent open dump disposal of glass waste. Interestingly, we can see that only the transportation providers of glass entering the landfill participate. For these providers, the prices in Scenario II allow finding positive profits because they are greater than the bids. Therefore, glass waste is transported to the landfill only when the tax is involved. Otherwise, the waste is sent to open dump systems (scenario I). As in the case of plastic, we observe that the prices vary depending on the stakeholder and not on the type of glass since the bids are equal for all types. We can see that the transportation providers make the smallest profits while the landfill suppliers attain the highest benefits. Regarding the type of glass, *G3* (corresponding to brown glass) represents most of the total profit. Comparing these results to those obtained for plastic, we observe that the profits for providers of glass are greater than the profits for providers of plastic. This is because of the different bids and flows of waste (more glass waste is generated).

4.4. Analysis for organic waste and non-recyclables

The figures referring to the profits for organic waste and non-recyclables are shown in the **supplementary material section**. We only evaluate one type of each waste (see Fig. 2). For organic waste, we consider all types of paper-based products (such as card-

Table 3
Bids and clearing prices for landfill supply, landfill demand, and transportation providers for glass.

	Bids (USD/tonne)	Prices (USD/tonne)				
Landfill supply	***S1-S5***	***S1***	***S2***	***S3***	***S4***	***S5***
Scenario I	−12.35	0	0	0	0	0
Scenario II (with tax)	−12.35	−3.09	−3.07	−3.12	−3.13	−5.1
Landfill demand	***D1-D5***	***D1***	***D2***	***D3***	***D4***	***D5***
Scenario I	−12.35	−12.21	−12.24	−12.19	−12.18	−12.14
Scenario II (with tax)	−12.35	−15.31	−15.31	−15.31	−15.31	−17.24
Transportation providers (entering landfill)	***K1-K5***	***K1***	***K2***	***K3***	***K4***	***K5***
Scenario I	0.04	−12.21	−12.24	−12.19	−12.18	−12.14
Scenario II (with tax)	0.04	2.2	2.2	2.2	2.2	0.27

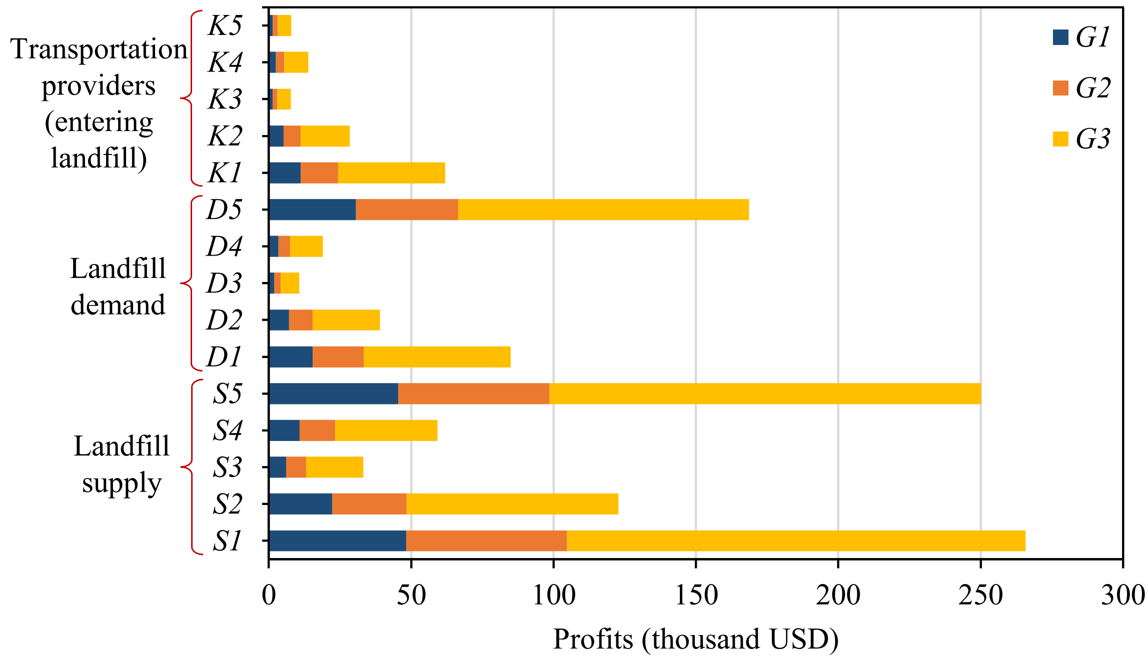

Fig. 5. Profits for landfill supply, landfill demand and transportation providers by types of glass in Scenario II.

board). While for non-recyclables, food waste is considered. No transformation providers participate in the optimal solution for these types of waste. For both organic waste and non-recyclables, their bids and clearing prices for the landfill supply are equal to those obtained for plastic. The same occurs with their bids and prices for the landfill demand (see Table 1). However, their profits are different due to the involved flows. Regarding the transportation providers of organic and non-recyclable waste entering the sanitary landfill, their bids and prices are also equal to those obtained for plastic (see Table 1) and, thus, the waste is transported to sanitary landfills. We observe positive profits for all landfill stakeholders only in Scenario II. Importantly, this indicates that taxation is necessary to activate the market and foster the participation of landfill providers to avoid open dump disposal. On the other hand, in Scenario I, all organic waste and non-recyclables are disposed of at open dumps and no participant makes a profit. For the profits of these types of waste in scenario II, the same trends found for plastic are observed. For instance, stakeholders 1 and 5 of every service (supply, demand, and transport) obtain greater profits than the other providers. Furthermore, all landfill suppliers attain the highest profits. We also observe that the profits for the participants of non-recyclables are slightly higher than those obtained for the stakeholders of organic waste.

It is important to note that in Scenario II, for every type of waste (plastic, metal, organic, glass, and non-recyclables), nothing is disposed of at open dumps. This occurs due to the involved taxation (5.1 USD/tonne). This tax was identified as the minimum penalization that avoids diverting waste (of all types) to open dumps. Lower taxes allow sending only some types of waste to sanitary landfills. However, this partial improvement is not of interest since the aim is to eliminate open dump systems and promote appropriate waste management.

Note that metal is the only type of waste that involves transformation providers (for both scenarios). Regarding the metal that is not recycled, in scenario I, it is disposed of at open dumps, while in scenario II it is disposed of at sanitary landfills (equally to the other types of waste). Specifically, 36% of the generated metal is processed in a treatment facility for sale. As mentioned above, the collective profit of the system is positive in all cases. Contrary to the study reported by Santibañez-Aguilar et al. (2013), where the recycled metal is maximized (100% is recycled), but the total profit is negative (this is not a coordinated approach).

5. Conclusions

This paper has presented a coordinated market framework for an MSW system. Here, different stakeholders were identified, including suppliers, consumers, as well as transportation and transformation providers. Each of these offers different bids and, through the solution of the problem, their clearing prices and profits are obtained. Furthermore, the possibility of sending waste to sanitary landfills or plants for treatment is considered. The waste ending up in open dumps is involved as well. A tax is included in the formulation to monetize this environmental impact. We show that this has the effect of activating the market and preventing open dump disposal. To show the applicability, an MSW system in Mexico was evaluated as a case study. However, the presented model is general and can be applied to any case study. Results show the allocations and prices that maximize the collective profit for all stakeholders and types of waste involved in distinct scenarios (with and without taxation). An important benefit of the proposed framework is that the clearing process guarantees that the individual profits are non-negative by balancing supply and demand for waste and products. The minimum tax required to avoid waste in open dumps was identified through the marginal values. Also, we found that the only type of waste that allows profitable recycling is metal. The proposed system in this approach results of special interest in regions where MSW collection is not efficient and MSW management needs to be greatly improved. Therefore, starting points such as including taxation to eliminate open dumps and considering the profits of all stakeholders to find a profitable system were addressed here. As part of future work, an analysis that includes varying bids of recyclables based on clearing prices could be interesting. Besides, we focused on the impact of open dump systems, but the approach can be extended to include other environmental issues.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2020.07.006.

References

Botello-Álvarez, J.E., Rivas-García, P., Fausto-Castro, L., Estrada-Baltazar, A., Gomez-Gonzalez, R., 2018. Informal collection, recycling and export of valuable waste as transcendent factor in the municipal solid waste management: A Latin-American reality. J. Clean. Prod. 182, 485–495. https://doi.org/10.1016/j.jclepro.2018.02.065.

Das, S., Lee, S.H., Kumar, P., Kim, K.-H., Lee, S.S., Bhattacharya, S.S., 2019. Solid waste management: Scope and the challenge of sustainability. J. Clean. Prod. 228, 658–678. https://doi.org/10.1016/j.jclepro.2019.04.323.

Garibay-Rodriguez, J., Laguna-Martinez, M.G., Rico-Ramirez, V., Botello-Alvarez, J.E., 2018. Optimal municipal solid waste energy recovery and management: A mathematical programming approach. Comput. Chem. Eng. 119, 394–405. https://doi.org/10.1016/j.compchemeng.2018.09.025.

Gutberlet, J., 2015. Cooperative urban mining in Brazil: Collective practices in selective household waste collection and recycling. Waste Manag. 45, 22–31. https://doi.org/10.1016/j.wasman.2015.06.023.

He, M., Jin, Y., Zeng, H., Cao, J., 2020. Pricing decisions about waste recycling from the perspective of industrial symbiosis in an industrial park: A game model and its application. J. Clean. Prod. 251,. https://doi.org/10.1016/j.jclepro.2019.119417 119417.

Hoornweg, D., Bhada-Tata, P., 2012. What a waste: a global review of solid waste management. https://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf (accessed February 2020).

Jiang, P., Fan, Y. Van, Zhou, J., Zheng, M., Liu, X., Klemeš, J.J., 2020. Data-driven analytical framework for waste-dumping behaviour analysis to facilitate policy regulations. Waste Manag. 103, 285–295. https://doi.org/10.1016/j.wasman.2019.12.041.

Ko, S., Kim, W., Shin, S.C., Shin, J., 2020. The economic value of sustainable recycling and waste management policies: The case of a waste management crisis in South Korea. Waste Manag. 104, 220–227. https://doi.org/10.1016/j.wasman.2020.01.020.

Lavee, D., 2007. Is municipal solid waste recycling economically efficient?. Environ. Manage. 40, 926–943. https://doi.org/10.1007/s00267-007-9000-7.

Lavee, D., Regev, U., Zemel, A., 2004. Optimal intervention in uncertain waste recycling markets, Monaster Center for Economic Research, Ben-Gurion University of the Negev, Israel

Lavee, D., Regev, U., Zemel, A., 2009. The effect of recycling price uncertainty on municipal waste management choices. J. Environ. Manage. 90, 3599–3606. https://doi.org/10.1016/j.jenvman.2009.06.012.

Lee, C.K.M., Yeung, C.L., Xiong, Z.R., Chung, S.H., 2016. A mathematical model for municipal solid waste management – A case study in Hong Kong. Waste Manag. 58, 430–441. https://doi.org/10.1016/j.wasman.2016.06.017.

Lohri, C.R., Camenzind, E.J., Zurbrügg, C., 2014. Financial sustainability in municipal solid waste management – Costs and revenues in Bahir Dar, Ethiopia. Waste Manag. 34, 542–552. https://doi.org/10.1016/j.wasman.2013.10.014.

Medina, M., 2010. Solid wastes, poverty and the environment in developing country cities: Challenges and opportunities. (No. 2010/23). WIDER Working Paper. UNU-WIDER, Helsinki. https://doi.org/10.1093/acprof:oso/9780199590148.003.0015

Minoglou, M., Komilis, D., 2013. Optimizing the treatment and disposal of municipal solid wastes using mathematical programming - A case study in a Greek region. Resour. Conserv. Recycl. 80, 46–57. https://doi.org/10.1016/j.resconrec.2013.08.004.

Mohammadi, M., Jämsä-Jounela, S., Harjunkoski, I., 2019. Sustainable supply chain network design for the optimal utilization of municipal solid waste. AIChE J. 65,. https://doi.org/10.1002/aic.16464 e16464.

Ojeda-Benitez, S., Beraud-Lozano, J., 2003. The municipal solid waste cycle in Mexico: final disposal. Resour. Conserv. Recycl. 39, 239–250. https://doi.org/10.1016/S0921-3449(03)00030-2.

Paul, K., Chattopadhyay, S., Dutta, A., Krishna, A.P., Ray, S., 2018. A comprehensive optimization model for integrated solid waste management system: A case study. Environ. Eng. Res. 24, 220–237. https://doi.org/10.4491/eer.2018.132.

Paut Kusturica, M., Golocorbin-Kon, S., Ostojic, T., Kresoja, M., Milovic, M., Horvat, O., Dugandzija, T., Davidovac, N., Vasic, A., Tomas, A., 2020. Consumer willingness to pay for a pharmaceutical disposal program in Serbia: A double hurdle modeling approach. Waste Manag. 104, 246–253. https://doi.org/10.1016/j.wasman.2020.01.029.

Sampat, A.M., Hu, Y., Sharara, M., Aguirre-Villegas, H., Ruiz-Mercado, G., Larson, R.A., Zavala, V.M., 2019. Coordinated management of organic waste and derived products. Comput. Chem. Eng. 128, 352–363. https://doi.org/10.1016/j.compchemeng.2019.06.008.

Santibañez-Aguilar, J.E., Ponce-Ortega, J.M., Betzabe González-Campos, J., Serna-González, M., El-Halwagi, M.M., 2013. Optimal planning for the sustainable utilization of municipal solid waste. Waste Manag. 33, 2607–2622. https://doi.org/10.1016/j.wasman.2013.08.010.

Semarnat, 2012. Informe de la Situación del Medio Ambiente en México. Compendio de Estadísticas Ambientales. Indicadores Clave y de Desempeño Ambiental. México. https://apps1.semarnat.gob.mx:8443/dgeia/informe15/tema/pdf/Informe15_completo.pdf (accessed January 2020).

Yousefloo, A., Babazadeh, R., 2020. Designing an integrated municipal solid waste management network: A case study. J. Clean. Prod. 244,. https://doi.org/10.1016/j.jclepro.2019.118824 118824.