MUNICIPAL SOLID WASTE MANAGEMENT USING A COORDINATED MARKET FRAMEWORK

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Abstract

The management of municipal solid waste (MSW) is still a world-wide challenge. For instance, in some countries, large amounts of waste end up in open dumps. The increasing generation of waste along with the lack of infrastructure and coordination between stakeholders make optimal MSW management challenging. This work proposes a coordinated market framework to accommodate multiple key stakeholders (e.g., suppliers of waste, consumers of waste and derived products, and providers of transportation and processing services) in MSW systems. The framework aims to find an optimal solution to facilitate appropriate MSW management. Here, the stakeholders submit bids to a coordinator that solves an optimization problem to determine allocations and clearing prices that maximize the collective profit and balance supply and demand for waste and products. This clearing process guarantees that no stakeholder loses money (the individual profits are non-negative). Furthermore, the framework facilitates the integration of policy incentives and the monetization of environmental impacts. We evaluated an MSW system in Mexico as a case study. Results reveal that taxation can incentivize the provision of services for all stakeholders and avoid open dump disposal.

Keywords

Municipal Solid Waste, Coordinated Framework, Taxation.

Introduction

The lack of infrastructure to collect, process, and dispose of MSW makes its management challenging. Particularly in developing countries, the lack of this type of systems has led to great environmental issues including open dump disposal. The Mexican environmental protection agency 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, 2015). There are several environmental, social, and safety impacts of open dump systems. These systems do not have the technologies of controlled landfills (e.g., leachate treatment, geological protection, and gas treatment). As a result, methane can leak into the environment and trigger fires. Also, strong leachates can pollute surface and groundwater. Food leftovers can attract wildlife which can transmit diseases to humans (Medina, 2010).

Some approaches have been proposed to address the MSW management problem. For instance, a taxation framework to incentivize recycling (Ko et al., 2020), a waste management cycle to guide policy regulations (Jiang et al., 2020), and mathematical models for the optimization of the MSW supply chain (Santibañez-Aguilar et al., 2013). A common problem for the MSW systems is the lack of coordination between the stakeholders involved. Recently, a general coordinated market framework for organic waste that facilitates transactions between multiple stakeholders was proposed by Sampat et al. (2019). This approach maximizes the collective profit of all the cleared stakeholders and can help monetize environmental impacts. The cleared stakeholders are the ones that participate in the market. The stakeholders that do not participate in the market as referred to as not cleared stakeholders.

In this work, we propose an optimization formulation for MSW management systems using a coordinated framework. We consider different common alternatives for the disposal of waste including recycling, sanitary landfills, and open dumps. In this system, the following stakeholders participate: i) urban centers that generate waste, ii) sanitary landfills that consume waste, iii) processing facilities that consume waste, iv) urban centers that consume derived products, v) transportation providers that move waste or products, and vi) transformation providers that treat different types of waste. From the coordinated framework perspective, these stakeholders are identified as suppliers and consumers of waste, consumers of products, and providers of transportation and processing technologies. We consider that the waste that is not allocated to consumers (sanitary landfills or processing

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facilities) ends up in open dumps. This practice is common in developing countries since there are no economic regulations associated with this action. Therefore, in the proposed formulation, we use the coordinated framework and include a taxation scheme to monetize this environmental impact.

Nomenclature

Parameters

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

Variables

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

Coordinated MSW Management System

Figure 1 shows the schematic representation of the system including the different stakeholders (consumers, suppliers, and providers) and possible pathways (sanitary landfills, open dumps, and treatment or recycling). Each stakeholder manages different types of waste or products at a specific geographical location (cities or urban centers). The stakeholders are categorized by the type of waste they handle (plastic, metal, organic, glass, and non-recyclables). Furthermore, subtypes are involved in some waste (e.g., for glass, we consider clear, green, and brown glass).

Each urban center has a specific generation rate of waste as well as available sanitary landfills, open dumps, and processing facilities for recycling. The transformation providers offer different types of treatment and technologies for each type of waste. The transportation providers can move waste to sanitary landfills and processing facilities, and products to final consumers. We also consider that the waste that is not sent to sanitary landfills or processing facilities is sent to open dumps. It is assumed that this type of disposal does not involve any economic cost. However, the environmental cost is considered through the proposed taxation scheme. This taxation scheme involves an economic penalization for the waste disposed of at open dumps. Within the coordinated framework, this tax is considered as a service that the environment provides to the waste suppliers. That is, the suppliers need to "pay" for the environmental impact of open dump disposal.

The coordinated framework guarantees that no stakeholder loses money because the payments collected are equal to the payments made. Here, the suppliers, consumers, and service providers submit bids to an independent system operator (ISO). This coordinator uses the bidding information to clear the market by identifying the optimal profits for all stakeholders. Clearing the market means finding the stakeholders and prices that balance supply and demand. These prices are denominated as clearing prices. An example of a market clearing process can be a system with 5 stakeholders and different bids. After solving the optimization problem that maximizes the collective profit and balances supply and demand, we could find, for instance, that only 3 stakeholders are cleared (they participate in the market). This optimal solution will include the clearing prices of all the cleared stakeholders. The optimal solutions provided by the ISO satisfy a set of economic properties. Some of these properties include competitive equilibrium, revenue adequacy, and transportation adequacy (Sampat et al., 2019).

The submitted bids to the ISO can be positive or negative. Almost all stakeholders offer positive bids which means that they provide their services only if they receive a payment. However, the sanitary landfills (consumers) offer negative bids. The negative bid of landfill consumers involves that the landfill will take the waste only if it is paid for this action (such as a disposal fee). This negative bid refers to a payment that landfill suppliers (urban centers) are willing to give the market for taking away their waste.

The ISO uses the submitted bids and solves an optimization problem to clear the market. In this formulation, the collective profit of all the cleared stakeholders (social welfare) is maximized. As part of the clearing process, the allocations, prices, and profits that balance supply and demand are found. Thus, all the individual profits of the cleared stakeholders are non-negative. It is considered that, when a stakeholder is not cleared, no product is allocated (this stakeholder does not participate in the market). The cleared stakeholders are paid based on their allocations and clearing prices. Specifically, transportation providers are paid considering the differences in prices at the source and destination locations. Similarly, the transformation providers are paid considering the prices of their input and output products.

Formulation of the Coordination Problem

The optimization formulation of the coordination problem is composed of different sets including geographical loca-

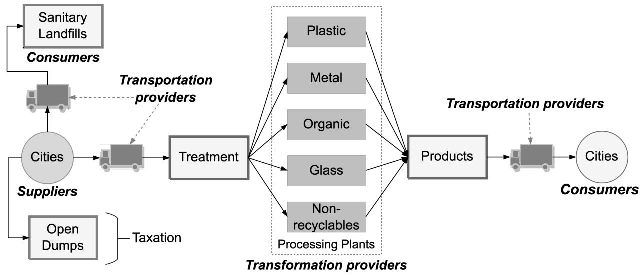

Figure 1: Schematic representation of the coordinated MSW system.

tions N, products P, consumers D, suppliers S, transportation providers K, and transformation providers M. The geographical locations refer to where waste is generated, where the products are consumed, and where sanitary landfills and processing plants are placed. The products represent the different types of waste and derived products obtained from the processing facilities. The suppliers are the urban centers that generate waste, while the consumers are the urban centers that demand waste (sanitary landfills) and useful products (from processing plants). 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. The processing providers refer to the different technologies to treat waste.

The bidding information (α_d, β_s, γ_k, δ_m) and the maximum capacities (c_d^*, g_s^*, q_k^*, f_m^*) of the stakeholders are given parameters. As shown in Eq. (1), the objective function seeks to maximize the collective profit of the cleared stakeholders. This profit is the difference between the demand served ($\alpha_d c_d$) and the costs of supply ($\beta_s g_s$), transportation ($\gamma_k q_k$), and transformation ($\delta_m f_m$). The solution to the problem includes finding the optimal allocations of each stakeholder: consumers (c_d), suppliers (g_s), transportation providers (q_k), and transformation providers (f_m) and prices that clear the market.

$$\max_{(d,s,q,f)} \sum_{d\in\mathcal{D}} \alpha_d c_d - \sum_{s\in\mathcal{S}} \beta_s g_s - \sum_{k\in\mathcal{K}} \gamma_k q_k - \sum_{m\in\mathcal{M}} \delta_m f_m \tag{1}$$

These allocations satisfy the physical conservation laws in Eq. (2), and capacity constraints in Eqs. (3)–(6). The clearing prices are also part of the solution and they are estimated through the dual variables ($\pi_{n,p}$). These variables act as market clearing prices because they set values for products P at each geographical location N. The dual variables are referred to as prices because they represent the economic value of products at the different locations. Here, $\zeta_{m,p}$ is the conversion factor for each technology and product.

$$\text{s.t.} \sum_{s\in\mathcal{S}_{n,p}} g_s - \sum_{d\in I\mathcal{D}_{n,p}} c_d + \sum_{k\in\mathcal{K}_{n,p}^{in}} q_k - \sum_{k\in\mathcal{K}_{n,p}^{out}} q_k + \sum_{m\in\mathcal{M}_n} \zeta_{m,p} f_m = 0, \quad (n,p)\in\mathcal{N}\times\mathcal{P}(\pi_{n,p}) \tag{2}$$

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

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

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

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

The allocations and prices are used to remunerate providers and charge consumers. This leads to revenue adequacy, which means that the payments collected are equal to the payments made. We use the notation π_d, π_s, π_k, π_m to refer to the marginal or clearing prices of each stakeholder at each location and for each product. We use the clearing prices, the bids, and the allocations to estimate the profits of stakeholders as follows. For consumers, $\alpha_d c_d$ refers to the monetary value of the allocated demand, and $\pi_d c_d$ is the payment made to the market. Thus, the profit for consumers (ϕ_d^D) is estimated by the difference between these values (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 $\pi_q q_k$ 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.

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

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

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

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

The clearing process guarantees that all the profits of the cleared stakeholders are non-negative (no stakeholder loses money), this is a key benefit of the coordinated framework.

Results and Discussion

We apply the proposed formulation to a case study that seeks to analyze how an MSW system would operate in the central-west region of Mexico. Five urban centers are considered: Morelia, Celaya, Apatzingan, Lazaro Cardenas, and Leon. These cities act as suppliers and consumers. Following the nomenclature from the model formulation, the different participants are identified as follows: S for suppliers, D for consumers, K for transportation providers, and M for processing providers. We use the notation 1-5 to refer to where the stakeholders are located. For instance, the technology provider $M1$ is situated in the city of Morelia.

Each stakeholder has a specific flow, product type, capacity, location, and bidding cost. The possible pathways for the generated waste are a processing facility for treatment, a sanitary landfill, and an open dump (which includes an economic penalization or tax). Also, we assume that i) the urban centers have equal technologies locally available to treat each type of waste (plastic, metal, organic, glass, and non-recyclables), and ii) landfill suppliers (which generate waste) are willing to pay for the service of taking away their waste. These assumptions are based on the current MSW management system. For the taxation scheme, the minimum tax required to avoid open dump disposal was identified and evaluated for the case study. To compare the impact of the taxation, two scenarios were analyzed. We consider Scenario I): a base case without taxation in which the impact of open dumps is ignored, and Scenario II): a tax is applied to the waste disposed of at open dumps. The evaluated tax in this case study is 5.1 USD/tonne; this value was identified as the minimum penalization that avoids diverting waste to open dumps. The procedure to obtain this minimum tax is as follows, we first evaluated a tax equal to 12.35 USD/tonne because this value is the cost of sending waste to the landfill. 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. Currently, there is not a well-established taxation scheme in the region of the case study. However, there are some examples of penalization schemes for open waste disposal in other regions. For instance, Illinois, there is a penalty of 1,500 USD for causing open dumping (Illinois Environmental Protection Agency, 2022). This highlights the feasibility of using the proposed tax to inform policy.

For the plastic, organic, glass, and non-recyclable waste, we found that no transformation providers participate (for both scenarios). Therefore, the only type of waste sent to treatment is metal waste. For Scenario I, there is no waste sent to the landfills and open dump disposal occurs. On the other hand, for scenario II, the waste is sent to sanitary landfills, and open dump disposal is avoided because of the taxation. In the following, we present some of the obtained results.

Analysis for plastic waste

For plastic waste, the stakeholders related to recycling are not cleared. Thus, there is no waste sent to treatment in both scenarios. In Scenario I, there is no plastic sent to the sanitary landfill and all plastic waste ends up at open dumps. However, when we apply the tax to open dump disposal (Scenario II), all plastic waste is sent to sanitary landfills.

Figure 2 presents the profits of the stakeholders that participate to send the plastic waste to landfills in Scenario II. The stakeholders are identified by their activity and location: landfill suppliers ($S1$-$S5$), landfill consumers ($D1$-$D5$), and transportation providers ($K1$-$K5$). The different types of plastic that each stakeholder can manage are denoted by $R1$-$R5$. The results show that stakeholders 1 and 5 always make the largest profits followed by stakeholders 2 and 4; while stakeholder 3 makes the smallest profit. This result is related to the location of the stakeholders. Regarding the types of plastic, $R1$ and $R2$ (corresponding to PP and PE) represent most of the total profit. Overall, we can see that the taxation scenario avoids diverting waste to open dumps by clearing landfill providers.

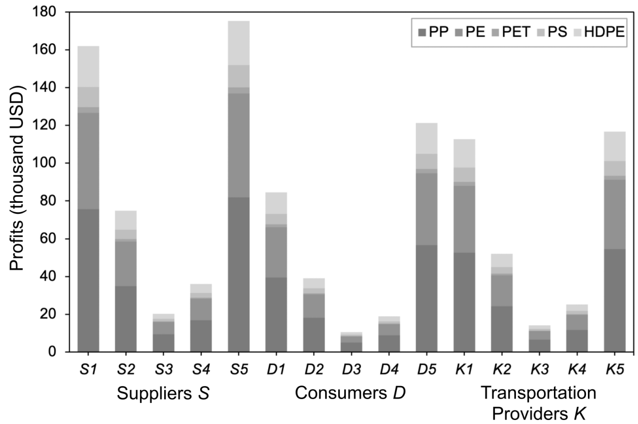

Figure 2: Profits for the landfill suppliers ($S1$-$S5$), consumers ($D1$-$D5$), and transportation providers ($K1$-$K5$) by types of plastic ($R1$-$R5$) in Scenario II.

Analysis for metal waste

Part of the metal waste is sent to recycling (40%) in both scenarios. However, in Scenario I, the other 60% is sent to open dumps. In this scenario, the landfill providers do not participate and only the stakeholders that participate in the processing of waste have positive profits. As shown in Figure 3, the processing plant suppliers and consumers are cleared as well as the transportation providers required to move waste and products. The processing provider $M1$ is also cleared. For Scenario II, 40% of the waste is sent to recycling too and the rest is sent to sanitary landfills because of the applied tax. Here, the landfill suppliers have positive profits as well as the stakeholders that process the waste.

As expected, the profits of the plant supply are the highest. We can see that only one plant consumer is cleared ($D1$). For the transportation providers, the profits are greater for Scenario I because no metal is sent to the landfill. The profits for the transformation providers do not change with the taxation scenario since the tax is not involved in the recycled waste.

Analysis for glass waste

No processing stakeholders participate here (as in the case of plastic waste). In Scenario, I there is no glass sent to the sanitary landfill and all waste is diverted to open dumps. However, the results of Scenario II reveal that the taxation scenario incentivizes the generation of landfill demand to prevent open dump disposal of glass waste. Thus, all the cleared stakeholders are related to the landfill disposal. Figure 4 shows the profits of these stakeholders. Here, we observe that the transportation providers attain the smallest profits. On the contrary, the landfill suppliers make the highest profits. We can see that stakeholders $S1$ and $K1$ attain the highest benefits of the suppliers and providers, respectively. For the consumers, the stakeholder $D5$ makes the highest profit. Regarding the types of glass, $G3$ (corresponding to brown glass) represents most of the total profit. These results are similar in behavior to the solutions for plastic, organic, and non-recyclable waste since the same stakehold-

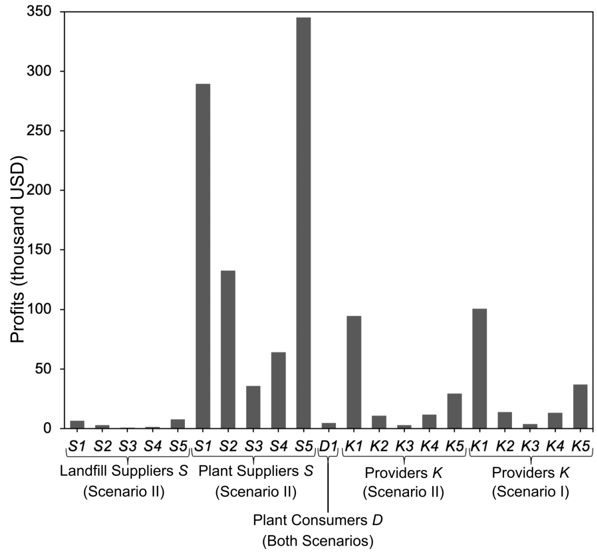

Figure 3: Profits for suppliers ($S1$-$S5$), consumers ($D1$), and transportation providers ($K1$-$K5$) of metal for Scenarios I and II.

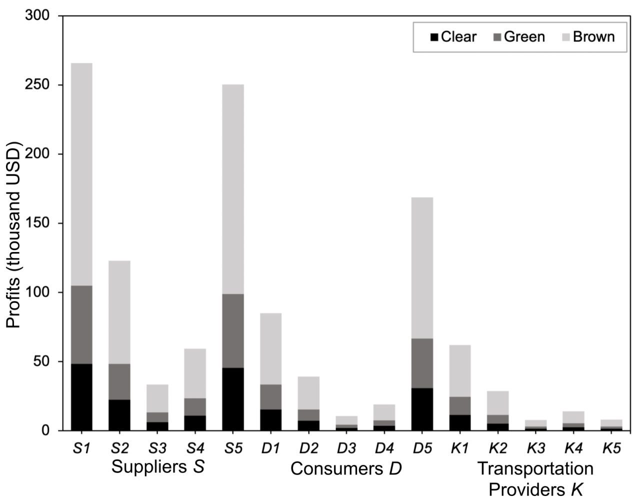

Figure 4: Profits for the landfill suppliers ($S1$-$S5$), consumers ($D1$-$D5$), and transportation providers ($K1$-$K5$) by types of glass ($G1$-$G3$) in Scenario II.

ers are cleared. The specific profits vary due to the involved flows, bids, and prices. However, through the presented results we intend to illustrate the type of solutions that can be obtained using the coordinated framework.

Conclusions

This work presented a formulation for the optimal management of MSW systems using a coordinated framework that accommodates multiple stakeholders. The involved stakeholders were suppliers, consumers, and providers of transportation and transformation. The evaluated pathways for the generated waste were treatment, sanitary landfills, and open dumps. We included a scenario with a taxation scheme to monetize the environmental impact of open dump disposal. We analyzed two different scenarios I): a base case without taxation and II): the taxation case where an economic penalization is applied to the waste disposed of at open dumps.

We evaluated a case study of an MSW in the central-west region of Mexico to show the applicability of the formulation. Through the proposed formulation, we found the optimal prices and allocations for the stakeholders. Also, the individual profits were identified (all of them non-negative). The results showed that taxation has the effect of activating the market and preventing open dump disposal.

The clearing process of the coordinated framework provided individual profits that 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 approach is of special interest in regions where MSW collection is not efficient and MSW management needs to be greatly improved. Therefore, we considered starting points such as including taxation to eliminate open dumps. Besides, the approach can be extended to monetize other environmental impacts.

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