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Research article

Monetary valuation of unsorted waste: A shadow price approach

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ABSTRACT

Improving the management of municipal solid waste (MSW) is fundamental to promote circular economy and sustainability. Unsorted waste involves negative environmental impacts which often are ignored in economic feasibility studies due to its difficult valuation. In this study the shadow price of unsorted waste using the directional distance function was estimated. This methodological approach also allowed us to compute eco-efficiency scores of a set of municipalities in the provision of MSW services. The empirical application focused on a sample of 119 Chilean municipalities. The results showed that the average shadow price of unsorted waste was 297.66 €/ton which means that the environmental cost of left waste as unsorted was 297.66 € per ton. A regression tree model illustrated that population density, tourism intensity and the generation of waste per capita significantly influenced the shadow price of unsorted waste. Moreover, it was illustrated that Chilean municipalities were very inefficient in the management of MSW since the average eco-efficiency score was 0.272. The findings from this study reveal that additional and alternative policies should be adopted to improve the management of MSW and increase its recycling rate.

1. Introduction

The provision of municipal solid waste (MSW) services evidences how developed a country is (Simoes et al., 2010). The current economic model functions under the assumption that resources are unlimited. This could result in higher rates of consumption and disposal of the products after minimal use (Medina-Mijangos et al., 2021). However, this behavior leads to an unsustainable situation for the environment and society. Economic growth, increased population density, new consumption habits and patterns could put more pressure in the existing resources and raw materials and increase the generation of solid waste (Simoes et al., 2012; Fan et al., 2020). It is estimated that by 2050 the generation of MSW could have grown to 3.40 billion tons from 2.01 billion tons which was in 2016 (Kaza et al., 2018). Moreover, poor management of MSW could be a risk for the environment and the health of people (Elagroudy et al., 2011). Thus, in recent decades the model of circular economy, where using less resources, reuse and recycle, has been promoted to deal with the increasing quantity of waste generated (Weng and Fujiwara, 2011).

The management of MSW involves the collection, transportation, recycle and disposal of waste. Municipalities aim to collect as much as recyclable waste (e.g., organic waste, paper, glass and plastic) as possible while trying to control their operating costs. As part of this process there might be several undesirable (bad) products that could be generated such as unsorted waste, which municipalities want to minimize as well (Sarra et al., 2017; Llanquileo-Melgarejo and Molinos-Senante, 2021). As a result, the growing interest of researchers and policy makers over the years has been focused on evaluating the efficiency of this process from an economic and environmental point of view (eco-efficiency). Additionally, quantifying the economic and environmental impacts (eco-impacts) of the waste management could be of great significance to policy makers to deliver the waste services in an efficient and sustainable manner (Romano and Molinos-Senante, 2020; Lo Storto, 2021; Delgado-Antequera et al., 2021; Amaral et al., 2022).

The interest to quantify the external benefits of recycling MSW has been increasing over the years because when economic analysis is based on internal impacts only, i.e., impacts with market value, this can involve biased results against more sustainable alternatives such as recycling (Haraguchi et al., 2019; Medina-Mijangos et al., 2021). However, most of the impacts associated with increasing the recycling

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rates of MSW are not easily quantified (Weng and Fujiwara, 2011). According to OECD (2006), economists have developed a range of methods to calculate the economic value of non-market impacts. They can be summarized into three main approaches: i) stated preference methods which use surveys for knowing the willingness to pay of respondents (e.g., Sarkhel et al., 2016; Maskey and Singh, 2017); ii) revealed preference methods that use existing markets for monetary valuation of intangible products or impacts (e.g., Demesouka et al., 2013; Kipperberg et al., 2019) and; iii) cost-based methods which estimate the economic value based on the economic cost of recovering the system from the negative impact suffered (e.g., Mazzanti and Montini, 2014; Pavón and Rizzi, 2019). In the framework of MSW services, an extensive literature review conducted by Feitosa et al. (2017) evidenced that most of previous studies employing the willingness to pay method for calculating positive externalities of improving MSW services.

Alternatively to the above cited methodological approaches to value externalities, Fare et al. (1989) proposed a novel method for valuing environmental externalities. This method is based on the framework of efficiency analysis and uses distance functions to estimate a shadow price of undesirable outputs where market prices do not exist. As it has been stated previously, in the framework of MSW services, unsorted waste can be considered as an undesirable output (Llanquileo-Melgarejo and Molinos-Senante, 2021). The estimated shadow prices have an environmental and economic interpretation. On the one hand, shadow prices can be interpreted as the environmental damage avoided if the undesirable outputs (unsorted waste) are managed efficiently or in other words, the environmental benefit gained from the collection and recycling process (Hernandez-Sancho et al., 2010). On the other hand, shadow prices could be considered as the extra spend in operating costs required to deal with the undesirable output. The distance function approach has been used to estimate the shadow price or environmental externalities associated with several pollutants such as carbon emissions (e.g., Molinos-Senante et al., 2015; Ma et al., 2019; Deng and Du, 2020; Sala-Garrido et al., 2021); atmospheric pollutants (e.g., Lee and Zhou, 2015; Zhang et al., 2020; Ji et al., 2021) and water pollutants (e.g., Hernandez-Sancho et al., 2010; Bellver-Domingo et al., 2017, 2018). However, to the best of our knowledge, the use of distance functions to estimate the environmental externalities of improving the management of unsorted waste has received limited attention.

Another relevant positive feature of the distance function method is its ability to evaluate the eco-efficiency of the units evaluated, i.e., the eco-efficiency of the municipalities in the provision of MSW services (Sala-Garrido et al., 2021). Previous studies assessed the eco-efficiency of waste sector using parametric (econometric) and non-parametric (linear programming) techniques. The advantage of non-parametric techniques over parametric ones is that they do not need to specify a functional form for the estimation of the production technology (Coelli et al., 2005). However, non-parametric techniques do not incorporate statistical noise in eco-efficiency assessment. To overcome the limitations of both methodological approaches, in this study we use a mix of parametric and non-parametric techniques to explore the eco-efficiency of the MSW sector by including both desirable and undesirable products.

Within this context, the objectives of our study are as follows. The first objective is to estimate the monetary value of the environmental externalities associated with the management of unsorted waste using the directional distance function approach. This allows quantifying the economic value of environmental externalities avoided by the collection and recycling process. Policy makers have the opportunity to understand how much it costs to avoid one extra unit of undesirable product being generated in the waste sector. For better understanding on what could influence the shadow price of unsorted waste, a regression tree model was applied to identify and visualize factors such as population density and waste generated per inhabitant (per capita) that were related to the shadow price of unsorted waste. The second objective is to assess the eco-efficiency of a sample of municipalities in the provision of MSW services. This allows managers to identity best and worst performers in the industry. While the assessment of eco-efficiency of the MSW sector has been researched in developed countries (see for instance, Simoes and Marques, 2012; Sarra et al., 2017; Guerrini et al., 2017; Exposito and Velasco, 2018; Romano and Molinos-Senante, 2020), it has received limited research in developing countries. Hence, the empirical approach focuses on the collection and recycling services in the municipal solid waste sector in Chile, an emerging country which has implemented several interesting policies to enhance MSW recycling[1] (Valenzuela-Levi et al., 2021). To the best of our knowledge, only, Molinos-Senante et al. (2022) used an input distance function to estimate the technical efficiency of a sample of municipalities in the provision of waste services and to compute the shadow price of unsorted waste. Nevertheless, Molinos-Senante et al. (2022) present two main limitations which our study overcomes. Firstly, they used an input distance function rather than a directional distance function as our study does. Hence, they focused on minimizing operational costs of providing waste services whereas our methodological approach allows simultaneously minimizing costs and unsorted waste and maximizing recyclable waste. Moreover, Molinos-Senante et al. (2022) did not evaluate the potential influence of exogenous variables on the shadow price of unsorted waste. To overcome these limitations, this is the first study, which combines eco-efficiency analysis techniques using a directional distance function approach to estimate the shadow price of undesirable outputs from the provision of waste services and decision tree techniques to understand its relationship with a set of environmental variables.

The paper unfolds as follows. The next section outlines the methodology followed by a description of the data and variables used in the study. Section 4 presents the findings of our case study, whereas the final section concludes.

2. Methodology

In this section we discuss the methodological approach used to calculate the shadow price of unsorted waste for a sample of Chilean municipalities. We also introduce the method employed to understand the effect of environmental variables on the shadow price of unsorted waste. The estimation of shadow price was undertaken using directional distance functions, an approach that was developed by Fare et al. (1993 , 2006). Distance function measures the maximal contraction of inputs (minimal expansion of outputs) keeping outputs (inputs) constant (Shephard, 1970). Directional distance function is a generalization of distance function that assume a simultaneous expansion of outputs and a reduction in inputs (Fare et al., 2005, 2012). Under this approach, it is assumed that municipalities are interested in collecting and recycling waste such as paper and glass, while at the same time want to minimize any undesirable products such as unsorted waste and inputs such as operating costs.

Our analysis starts with the introduction of production technology and definition of directional distance functions. Let's assume that municipalities produce a vector of desirable (good) outputs $y = (y_1, \ldots, y_K) \in R_+^K$ using a set of inputs $x = (x_1, \ldots, x_L) \in R_+^L$. During the production process, a set of undesirable (bad) outputs are produced as well, which are denoted as $b = (b_1, \ldots, b_M) \in R_+^M$. As a result, the production technology is defined as follows:

$$PT = \{(y, b) : x \text{ can generate } y \text{ and } b\} \quad (1)$$

The production technology fulfils the criteria of convexity and free disposability of inputs (Molinos-Senante et al., 2015). Additionally, it is assumed that both desirable and undesirable outputs are jointly generated as part of the production process. It is also assumed that good and bad outputs are weakly disposable (Fare et al., 2005). Finally, desirable products can be disposed without any extra cost, i.e., they are freely

[1] See Case study area section.

disposable (Sala-Garrido et al., 2021). Thus, the directional output distance function, $\overrightarrow{D_o}$ can be defined as follows (Färe et al., 2006):

$$\overrightarrow{D_o} = (x, y, b;\ g_y, -g_b) = max\{\varphi :\ (y + \varphi g_y, b - \varphi g_b) \in PT\} \tag{2}$$

where $g = (g_y, g_b)$ is the directional vector, the direction at which desirable outputs expand and undesirable outputs go down. A direction of $g = (1, -1)$ means that the good outputs expand and the bad outputs reduce at the same time (Bogetoft and Otto, 2011). This is the approach chosen in this study for the collection and recycling of both recyclables and unsorted waste. In the directional distance function in Eq. (2), φ measures inefficiency. This means that if φ is zero, then the unit (municipality) under assessment is on the efficient frontier, whereas any positive values of φ denote inefficiency. Since the municipalities in our study minimize both inputs and undesirable outputs, the derived efficiency can be considered as eco-efficiency (Beltrán-EsteveReig-Martínez and Estruch-Guitart, 2017). Eco-efficiency scores range between 0.0 and 1.0. A municipality is considered eco-efficient if and only if its score is 1.0 whereas it presents room to improve its eco-efficiency when its score is below 1.0. The difference between 1.0 and the eco-efficiency score of the evaluated municipality represents its potential to performance improvement.

Based on past studies (Fare et al., 1993, 2006) the duality relationship between revenue function and output directional distance function was employed for the estimation of the shadow price of undesirable output. In particular, the revenue function is presented as follows:

$$R(x, y, b) = max\{py - sb :\ (y, b) \in PT\} \tag{3}$$

In Eq. (3), p denotes the vector of prices for desirable products and s is the vector of prices for undesirable products. Based on a possible directional vector $g = (g_y, g_b)$ the revenue function can be expressed as follows:

$$R(x, y, b) \geq (py - sb) + p\overrightarrow{D_o}(x, y, b; g)g_y + s\overrightarrow{D_o}(x, y, b; g)g_b \tag{4}$$

In Eq. (4), $R(x, y, b)$ shows the maximum possible revenue, whereas the right part of this equation includes observed revenue and technical efficiency improvement which could be attributed to an expansion of desirable products along g_y and a reduction of undesirable products along g_b. After rearranging the terms in Eq. (4), we can get the directional output distance function as follows:

$$\overrightarrow{D_o}(x, y, b; g) = min\left\{\frac{R(x, p, s) - (py - sb)}{pg_y - sg_b}\right\} \tag{5}$$

Supposing that the revenue and directional distance functions are differentiable (Sala-Garrido et al., 2021), the first-order conditions regarding the good and bad products can be derived as follows:

$$\nabla_y \overrightarrow{D_o}(x, y, b; g) = \frac{-p}{pg_y - sg_b} \tag{6}$$

$$\nabla_b \overrightarrow{D_o}(x, y, b; g) = \frac{s}{pg_y - sg_b} \tag{7}$$

Based on Eqs. (6) and (7) and if the market price of kth desirable product is equal to its shadow price, p_k, then the shadow price of the mth undesirable product, i.e., unsorted waste, is defined as follows:

$$s_m = -p_k\left(\frac{\partial \overrightarrow{D_o}(x, y, b; g)}{\partial b_m} \Big/ \frac{\partial \overrightarrow{D_o}(x, y, b; g)}{\partial p_k}\right) \tag{8}$$

The estimation of the directional output distance function can be conducted using parametric and non-parametric techniques. Unlike parametric, non-parametric techniques such as Data Envelopment Analysis (DEA) do not assume a priori a functional form for the underlying technology such as translog and quadratic (Coelli et al., 2005; Ananda, 2018). However, the main disadvantage of non-parametric techniques is that the distance function is not differentiable so it cannot be used for the estimation of shadow prices (Färe et al., 2006; Du et al., 2015; Xie et al., 2017). Thus, this study uses a parametric approach where the production technology takes a particular functional and its parameters are derived using linear programming techniques. This study uses a quadratic functional form because, as Färe et al. (2006) noted, unlike translog, it does not violate the translation property of the directional output distance function (Molinos-Senante and Guzman, 2018). Thus, the parametric directional output distance function for the jth producer takes the following form (Wei et al., 2013; Hou et al., 2019)

$$\begin{aligned}\overrightarrow{D_o}(x_j, y_j, b_j; 1, -1) &= a_o + \sum_{l=1}^{L} a_l x_{lj} + \sum_{k=1}^{K} \beta_k y_{kj} + \sum_{m=1}^{M} \gamma_m b_{mj} + \frac{1}{2}\sum_{l=1}^{L} \\ &\times \sum_{l'=1}^{L} a_{ll'} x_{lj} x_{l'j} + \frac{1}{2}\sum_{k=1}^{K}\sum_{k'=1}^{K} \beta_{kk'} y_{kj} y_{k'j} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M} \gamma_{mm'} b_{mj} b_{m'j} + \sum_{l=1}^{L} \\ &\times \sum_{k=1}^{M} \delta_{lk} x_{lj} y_{kj} + \sum_{l=1}^{L}\sum_{m=1}^{M} \eta_{lm} x_{lj} b_{mj} + \sum_{k=1}^{K}\sum_{m=1}^{M} \mu_{km} y_{kj} b_{mj}\end{aligned} \tag{9}$$

The parameters of Eq. (9) are estimated by solving the following linear programming model:

$$Min \sum_{j=1}^{J}\left[\overrightarrow{D_o}(x_j, y_j, b_j; 1, -1) - 0\right] \tag{10}$$

$s.t.$

$$i)\ \overrightarrow{D_o}(x_j, y_j, b_j; 1, -1) \geq 0, j = 1, \ldots, J$$

$$ii)\ \frac{\vartheta \overrightarrow{D_o}(x_j, y_j, b_j; 1, -1)}{\vartheta y_k} \leq 0, k = 1, \ldots, K;\ j = 1, \ldots, J$$

$$iii)\ \frac{\vartheta \overrightarrow{D_o}(x_j, y_j, b_j; 1, -1)}{\vartheta b_m} \geq 0, m = 1, \ldots, M;\ j = 1, \ldots, J$$

$$iv)\ \frac{\vartheta \overrightarrow{D_o}(x_j, y_j, b_j; 1, -1)}{\vartheta x_l} \geq 0, l = 1, \ldots, L;\ j = 1, \ldots, J$$

$$v)\ \sum_{k=1}^{K} \beta_k - \sum_{m=1}^{M} \gamma_m = -1;\ \sum_{k'=1}^{K} \beta_{kk'} - \sum_{m=1}^{M} \mu_{km} = 0, k = 1, \ldots, K$$

$$\sum_{m'=1}^{M} \gamma_{mm'} - \sum_{k=1}^{K} \mu_{km} = 0, m = 1, \ldots, M$$

$$\sum_{l=1}^{L} \delta_{lk} - \sum_{m=1}^{M} \eta_{lm} = 0, l = 1, \ldots, L$$

$$vi)\ a_{ll'} = a_{l'l}\ l' \neq l;\ \beta_{kk'} = \beta_{k'k}\ k' \neq k;\ \gamma_{mm'} = \gamma_{m'm}\ m' \neq m$$

The first condition ensures that each unit under evaluation (i.e., municipality) is located below or on the efficient frontier. Conditions (ii) – (iv) ensure monotonicity for outputs and inputs. Condition v) imposes the translation property, whereas the last condition imposes symmetry (Sala-Garrido et al., 2021).

The next step of our analysis is to understand if the estimated shadow price of unsorted waste is affected by several environmental (explanatory) variables and quantify this impact. For this reason, a regression tree model is acquired by recursively separating the set of possible values for environmental (explanatory) variables and by giving a predicted (fitted) value for the output (shadow price of unsorted waste in our case) variable within each separation. Regression tree models can be displayed graphically, can include numerical and categorical values and can be understood by non-experts (Rebai et al., 2019).

The following two-steps are used to derive a regression tree model (James et al., 2013). In the first step, the observations are separated into T different and non-over lapping regions, $I_1, \ldots, I_T$. In the second step, for each observation that belongs to the region I_τ, the model gives a predicted (fitted) value for the output variable using the mean value, $\overline{\widehat{\omega_\tau}}$ of the observations in region I_τ (Rebai et al., 2019). The residual sum of squares (RSS) is minimized to choose the regions:

$$\sum_{\tau=1}^{T} \sum_{i \in I_\tau} \left(\widehat{\omega_i} - \overline{\widehat{\omega_\tau}}\right)^2 \tag{11}$$

A regression tree model has the following generic form:

$$f(\xi) = \sum_{\tau=1}^{T} \overline{\widehat{\omega_\tau}} \Xi_{(\xi \in I_\tau)} \tag{12}$$

where ξ is a set of environmental (explanatory) variables, T is the number of non-overlapping regions and $\overline{\widehat{\omega_\tau}}$ is the average value of the output variable that is derived based on the observations that belong to region I_τ.

Finally, as robustness check, a linear regression was performed using the same data and having the estimated shadow price of unsorted waste as the dependent variable and the environmental variables as independent (explanatory) variables.

3. Case study area

Our empirical approach focuses on the collection and recycling services provided by 119 municipalities in Chile. To improve the management of solid waste within the framework of circular economy, the Chilean Law 20920 was implemented in 2016. The main objective of this law is to reduce the generation of waste and promote reuse, recycling and recovery, through the establishment of extended producer responsibility and other instruments for waste management. This Law introduces both economic incentives and legal obligations for municipalities and private organizations to increase the recycling rate of solid waste in Chile which currently is below 10% (OECD, 2021). Moreover, other specific policies and laws have been implemented in Chile to reduce the generation of solid waste such as the Law 21100 which prohibits the delivery of plastic bags in commerce.

The data used was from the year 2018 and was taken from the National Waste Declaration System (SINADER) and National Municipal Information System (SINIM). The inputs, desirable and undesirable outputs were selected based on review of literature on waste sector and availability of data (Simoes et al., 2010; Guerrini et al., 2017; Romano and Molinos-Senante, 2020; Llanquileo-Melgarejo et al., 2021; Molinos-Senante and Maziotis, 2021). As far as the input was concerned, it was defined as operating costs of providing waste collection and recycling services (Marques and Simoes, 2009; Rogge and De Jaeger, 2013; Sarra et al., 2017; Romano and Molinos-Senante, 2020). Operating costs were expressed in Chilean pesos per year (Llanquileo-Melgarejo et al., 2021). The desirable output was defined as the total amount of recyclable products and was measured in tons per year. It was calculated as the sum of the quantity of paper, plastics, glass, organic and other organic waste collected and recycled (Bosch et al., 2000; García-Sánchez, 2008; Marques and Simoes, 2009; Exposito and Velasco, 2018). As for the undesirable output, it was defined as the quantity of unsorted waste measured in tons per year (Llanquileo-Melgarejo and Molinos-Senante, 2021; Molinos-Senante and Maziotis, 2021).

The environmental variables used to evaluate their impact on the shadow price of unsorted waste were defined based on the characteristics of the municipalities, previous literature and data availability (Simoes and Marques, 2011; Sarra et al., 2017; Romano and Molinos-Senante, 2020). The first environmental variable was population density (Halkos and Petrou, 2019; Romano et al., 2019; Agovino et al., 2020) defined as the ratio of the number of inhabitants and the area covered (Molinos-Senante and Maziotis, 2021). The second variable was a tourist index proposed by the Division of Studies and Territory of the Undersecretariat of Tourism which is a proxy of the tourism intensity. According to prior literature, tourism may affect eco-efficiency due to the marked increase in municipal solid waste generation as the seasonal population of tourists rises (Shamshiry et al., 2011; Mateu-Sbert et al., 2013). The third variable was defined as the total waste generated per inhabitant (per capita) and is calculated as the total quantity of waste collected measured in tons divided by the number of inhabitants of each municipality (Llanquileo-Melgarejo and Molinos-Senante, 2021).

In Table 1 we report the descriptive statistics of the variables used in the study.

4. Results and discussion

4.1. Eco-efficiency assessment

The estimation of the directional output distance function was carried out using the General Algebraic Modeling System with the CPLEX solver. The estimated parameters of the directional output distance function are reported in Table 2. Based on these parameters, we derived the eco-efficiency of each municipality in the provision of MSW services and the shadow price of unsorted waste. The basis statistics of them are reported in Table 3. It is found that the average eco-efficiency in the Chilean solid waste sector was substantially poor, 0.272. Taken into account that municipalities are eco-efficient when its score is 1.0, on average, municipalities needed to reduce their operating costs and unsorted waste by 63% to improve economic and environmental performance. The least efficient municipality reported an eco-efficiency score of 0.099, whereas the most efficient municipality did not have an eco-efficiency score greater than 0.30. This finding suggests that none of the municipalities was full eco-efficient and therefore all of them have notably room to improve its performance.

Fig. 1 presents the distribution of eco-efficiency scores across municipalities. It is found that the majority of Chilean municipalities evaluated had an average eco-efficiency which ranged between 0.26 and 0.30. This means that considerable inefficiency exists in the Chilean solid waste sector. On average the potential savings in operating costs and unsorted waste among municipalities amount to the level of 70%, while trying to collect as much recyclable products as possible. The results are consistent with previous studies by Llanquileo-Melgarejo et al. (2021) and Llanquileo-Melgarejo and Molinos-Senante (2021) who

Table 1
Descriptive statistics.

Variables	Unit of measurement	Mean	Standard Deviation	Minimum	Maximum
Total costs[a]	€/year	2008.16	2756.38	78.3	15134.80
Total recyclable waste	Tons/year	1715	5356	9	36705
Unsorted waste	Tons/year	43,141	57,028	277	368,104
Total waste generated per inhabitant	Ton/ inhabitant * year	0.175	0.953	0.000	1.069
Population density	Inhabitants/ km[a]	1129	3206	0.311	18,386
Tourist index	Index	0.051	0.113	0.001	1.000

Number of observations: 119.
[a] The conversion rate on July 8, 2022 was 1 € ≅ 975.60 CLP.

Table 2
Estimated parameters of the directional output distance function.

Coefficient	Value
α_o	−2.794
α_1	0.007
β_1	−0.976
γ_1	0.024
$\alpha_{1,1}$	0.000
$\beta_{1,1} = \gamma_{1,1} = \mu_{1,1}$	0.000
$\delta_{1,1} = \eta_{1,1}$	0.000

Table 3
Summary statistics of eco-efficiency scores and shadow price of unsorted waste.

	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Eco-efficiency	Score	0.272	0.034	0.099	0.288
Shadow price of undesirable output	€/ton	297.66	373.186	0.045	2536.46

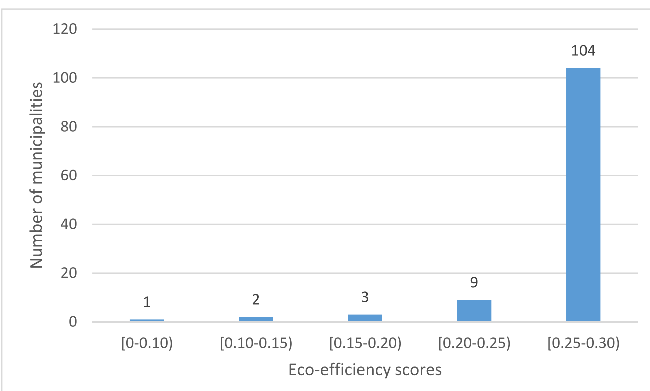

Fig. 1. Distribution of eco-efficiency scores across municipalities.

reported low efficiency scores for the Chilean waste sector using non-parametric techniques. In particular, 73% of municipalities reported an average cost efficiency score of less than 0.2, whereas an average eco-efficiency of 0.5 was found for most of them. The findings of the above studies were corroborated by Molinos-Senante and Maziotis (2021) who used econometric techniques to estimate the eco-efficiency of the Chilean waste sector. Eco-efficiency estimations for Chilean municipalities are not comparable with those computed for other countries because a basic premise of the frontier methods, such as the one use in this study, is that units evaluated perform under similar conditions (De Witte and Marques, 2009) which in the case of solid waste services corresponds to the same regulatory framework. Moreover, in our study the rest of the municipalities were found to have an eco-efficiency score less than 0.25 on average. In particular, 9 municipalities had an average eco-efficiency score which varied between 0.21 and 0.25. This means that these municipalities should reduce their operating costs up to 75% when non-recycle waste was incorporated in the analysis. Substantial reductions in costs and unsorted waste should be considered for the rest of municipalities. Improvements in economic and environmental performance require the reduction in costs and undesirable output up to 90% on average.

The eco-efficiency scores reported provide relevant information for the Chilean Environmental Ministry as they illustrate that the objectives of the Law 20920 have not been achieved yet and therefore, alternative and novel policies should be proposed and implemented to improve the management of MSW in Chilean municipalities. Given that none of the municipalities has been defined as fully eco-efficient, i.e., with an eco-efficiency score equal to 1, there is no reference unit whose practices could be studied and replicated to improve the eco-efficiency of the other municipalities. In this context, the policy makers should investigate practices and policies already implemented in other countries to improve MSW management in Chile in the following years.

4.2. Shadow price of unsorted waste

According to Eq. (8), the shadow price of unsorted waste was derived using the price of desirable output, i.e. recyclable products, as the reference price. As far as the shadow price of unsorted waste is concerned, as it is shown in Table 3, its average value was 297.66 Euros per ton. This means that the environmental benefit from dealing with any unsorted waste during the collection and recycling process could reach the level of 297.66 Euros per ton on average. Depending on the costs and the amount of recyclable and unsorted waste recycled, the environment damage avoided could range from 0.045 to 2536.46 Euros per ton per year on average. Based on an input distance function approach, Molinos-Senante et al. (2022) estimated an average shadow price of unsorted waste of 81 US \$ per kilogram (around 0.0828 Euros per ton). The minimum and maximum shadow prices reported were 0.81 US \$/Kg (8.3 * 10^{-4} Euros/ton) and 292.75 US \$/Kg (0.299 Euros/ton), respectively. It is revealed that shadow prices of unsorted waste estimated by Molinos-Senante et al. (2022) are notable lower than those reported in this study. It should be noted that the methodological approach used to estimate the shadow prices and the Chilean municipalities evaluated were different in both studies. It evidences the importance of using reliable and robust methods for shadow price computation and the relevance of local conditions on the management of MSW.

The distribution of the environmental benefits from managing unsorted waste across municipalities is displayed in Fig. 2. It is found that 35% of municipalities (42 out of 119) reported an average shadow price of unsorted waste which ranged from 0 to 100 Euros per ton. This means that on average, each ton of waste that is ended unsorted as consequence of the recycling and waste process, involved an environmental cost of up to 100 Euros per ton. There were several municipalities that could incur a higher environmental benefit. In particular, for 14 municipalities the environmental damage avoided if unsorted waste is adequately managed could range between 101 and 200 Euros per ton. Higher levels of environmental benefit were reported for the rest of the municipalities. 24 municipalities needed to spend an extra 201 to 300 Euros in operating expenditure to deal with one ton of unsorted waste. The implicit cost of reducing unsorted waste was considerably higher for 21 municipalities. This implies that these municipalities needed to spend more than 500 Euros in costs to prevent one ton of waste from not being sorted

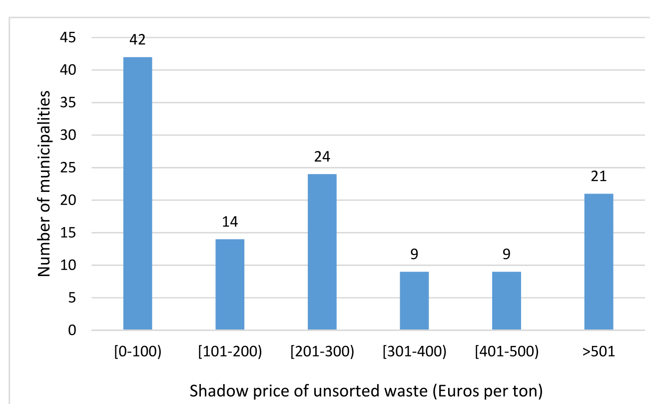

Fig. 2. Distribution of shadow price of unsorted waste (Euros per ton) across Chilean municipalities.

as part of the collection and recycling process. Overall, the findings suggest that the Chilean solid waste sector was characterized by high levels of eco-inefficiency. This had an impact on the shadow price of unsorted waste as the cost of reducing this undesirable product was found to be more than 500 Euros per ton. However, dealing with any unsorted waste is considered necessary as it can bring huge environmental benefits for the society and environment. This could be done, for instance, by having more frequent schedules in collecting waste, by installing more green points to collect recyclable products and by educating people on the benefits of recycling.

Economic accounting for implementing alternative MSW management systems should integrate the environmental benefits of reducing unsorted waste, i.e., the shadow prices estimated, to reflect the true value of increasing MSW recycling and thereby the environmental protection. From the point of view of decision-making process, the economic value of unsorted waste may be included within a feasibility analysis such as cost-benefit analysis to evaluate the economic feasibility of different models to manage MSW at local level (Bellver-Domingo et al., 2017).

Because estimated shadow prices of unsorted waste considerably varied across municipalities, it is worth discussing if location matters when providing waste services. The findings of this analysis are reported in Table 4. Population density across Chilean regions varies as it is shown in Table 4. There are several densely populated regions that are mainly located in the central and south parts of Chile. In those regions the shadow price of unsorted waste were among the highest in the study area. For instance, the region of Bio-Bio with a population density of 1479 inhabitants per km^2 was required to spend an extra 333 Euros in costs on average to avoid one ton of waste being unsorted. This area reported an average eco-efficiency of 0.279 which means that operating costs and unsorted waste could contract by 72% to improve economic and environmental performance. It appears that although the region is doing well in collecting recyclable waste as shown by the waste per inhabitant value, the amount of unsorted waste could potentially reduce to improve efficiency. Literature assessing the influence of population density on the performance of solid waste providers is inconclusive. On the one hand, some studies found that higher population density causes lower costs and therefore, higher efficiency (Guerrini et al., 2017; Exposito and Velasco, 2018; Llanquileo-Melgarejo and Molinos-Senante, 2021). On the other hand, other studies showed that higher density reduced efficiency of waste service providers (De Jaeger et al., 2011; Vishwakarma et al., 2012).

The south part of Chile reported the highest level of shadow price of unsorted waste. It is found that in the region of Ñuble the mean environmental damage avoided if unsorted waste is properly managed could be 791.63 Euros per ton. This region is characterized by high levels of unsorted waste and operating costs. This region could improve its eco-performance by putting more efforts in setting up more green points for the collection of recyclable materials. This is evident from the amount of recyclable waste per inhabitant which remained at low levels. Overall, the average environmental benefit from reducing any unsorted waste in the south part of Chile was considerably high and it could range from 183 to 792 Euros per ton. The potential savings in operating costs and unsorted waste among municipalities in the southern part of Chile could vary between 71.4% and 73% on average. Considerable environmental benefits from recycling any unsorted waste were apparent for the central part of Chile as well. These regions which include the capital of Chile are densely populated and highly touristic. These regions reported slightly lower levels of shadow price of unsorted waste compared to the southern regions. As these regions involve more municipalities and more inhabitants, the recycling and collection waste services might be of better quality. However, this might not always be the case. For instance, it is found that the Metropolitan region of Santiago reported an average eco-efficiency of 0.255. This means that while collecting more recyclable waste, the municipalities in this region could reduce their operating costs and unsorted waste by 74.5% on average. Better management of daily operations, for instance, through the use of more frequent waste collection services could improve eco-performance. Other densely populated areas such as the region of Maule reported higher levels of shadow price of unsorted waste. This region was required to spend an extra 450 Euros in costs on average to prevent one ton of waste remained unsorted. Less densely populated regions in the central part of Chile need to improve eco-performance as well. The potential savings in average costs and unsorted waste among the municipalities in the region of Coquimbo could reach the level of 73%. For this region, on average each ton of waste that is left unsorted as part of the waste process involved an environmental cost of 111.5 Euros on average. Thus, although this region is not very densely populated and not very touristic the potential environmental benefits for reducing any unsorted waste and improving eco-performance are substantial. In the central region of Chile the potential reduction in costs and unsorted waste could vary between 71.6% and 74.5% on average, whereas the environmental benefits from an efficient management of waste services could range between 111 and 450 Euros per ton on average. The north part of Chile appeared to be highly eco-inefficient in the study. This might be attributed to the fact that less densely populated areas are characterized by higher costs of providing collection and recycling services.

In order to get a better understanding on what could affect the shadow price of unsorted waste, we need to look into the results from the regression tree model which are reported in Fig. 3. The numbers at the bottom of each branch shows the mean shadow price of unsorted waste, while the percentage refers to the percentage of observations used in that particular branch to derive the mean shadow price. The findings are interpreted as follows. First, it is found that the total amount of waste generated per inhabitant, population density and tourist index influenced the mean shadow price of unsorted waste (see appendix – Fig. 1). In particular, the most important variable that affected the shadow price was the quantity of waste generated per capita. Moreover, if the collected and recycled waste increases by more than 0.015 ton per

Table 4
Eco-efficiency and shadow price of unsorted waste by Chilean region.

Region	Location	Number of muncipalities	Shadow price of unsorted waste (€/ton)	Eco-efficiency score	Density (inh/km^2)	Tourism index	Waste per inhabitant (Ton/inhabitant * year)
Araucanía	South	9	344.640	0.270	571.5	0.041	0.034
Bío-Bío	South	8	332.497	0.279	1479.4	0.038	0.194
Los Lagos	South	5	282.522	0.285	2772.2	0.023	0.022
Los Ríos	South	4	182.979	0.276	46.6	0.013	0.035
Ñuble	South	3	791.632	0.286	14.4	0.003	0.010
Antofagasta	North	1	235.951	0.115	32.95	0.004	0.102
Coquimbo	North	4	111.554	0.279	69.28	0.010	0.077
Libertador General Bernardo O′ higgins	Central	14	131.308	0.278	1662.5	0.045	0.085
Maule	Central	11	450.465	0.284	2060.0	0.021	0.015
Metropolitana de Santiago	Central	34	239.071	0.255	951.1	0.054	0.185
Valparaíso	Central	26	375.782	0.283	949.6	0.095	0.019

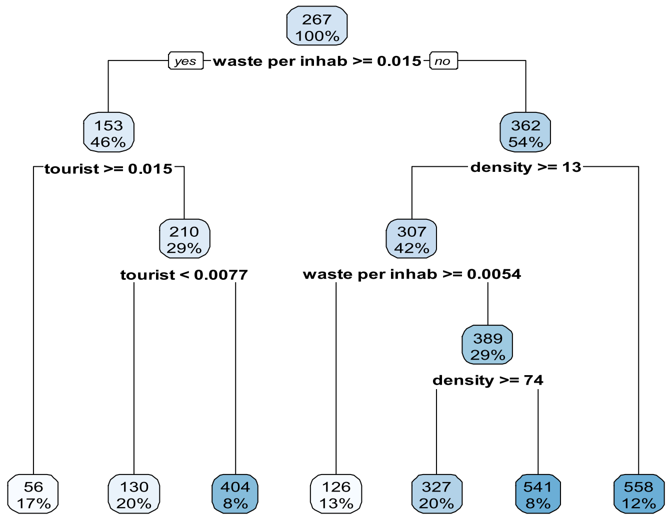

Fig. 3. Regression tree model: dependent variable is the shadow price of unsorted waste (Euros/ton).

inhabitant then the environmental damage avoided could be 153 Euros per ton as indicated by 46% of the municipalities (observations) employed in this study. Thus, the collection and recycling of more MSW could bring down the operating costs of municipalities in the long term. If these municipalities put efforts to collect more recycled waste in highly touristic areas (areas with a tourist index greater than 0.015), then the environmental cost of unsorted waste could be 56 Euros per ton. Therefore, it appears that collecting more MSW per capita in highly touristic regions could push down the cost of reducing any unsorted waste. However, municipalities who collect significant amounts of waste per capita in less touristic areas could experience higher levels of shadow price. For instance, municipalities who collect more than 0.015 ton of waste per capita in regions with a very low tourist index (less than 0.0077) are required to spend an extra of 404 Euros in costs to prevent one ton of waste being unsorted. In general, municipalities who collect and recycle considerable amounts of waste per capita (greater than 0.015 ton per inhabitant) in moderate tourist areas (tourist index less than 0.015) could experience an increase in operating costs by 210 Euros to deal with one ton of unsorted waste. Thus, for large amounts of waste generated per capita the touristic characteristics of the region could influence the shadow price of unsorted waste.

Delving into the right part of the regression tree model, it is concluded that if the municipalities do not put efforts to collect large amounts of MSW per capita (less than 0.015 ton per inhabitant), then the shadow price of unsorted waste could increase at the level of 362 Euros per ton which is supported by 54% of municipalities (observations) in the study. In this case, population density plays a crucial role in the level of shadow price. In particular, municipalities who collect and recycle less than 0.015 ton of waste per capita in regions whose population density is less than 13 inhabitants per km^2, then the environmental cost of unsorted waste could reach the level of 558 Euros per ton. This finding means that it is very costly to provide collection and recycling waste services to less densely populated areas. For more densely populated areas, with a density of more than 13 inhabitants per km^2, the shadow price of unsorted waste is lower but still at high levels, 307 Euros per ton. In those densely populated areas, if the municipalities collect and recycle more than 0.0054 ton of waste per capita, then the extra spend in operating costs to avoid one ton of unsorted waste could be at the level of 126 Euros. This finding implies that it is less costly to provide waste services to densely populated areas. However, in those regions if the amount of waste per capita is considerably low, less than 0.0054 ton per inhabitant, then, on average each ton of unsorted waste entails a considerable environmental cost of 389 Euros. This could further increase if the regions become even more densely populated. In particular, poor levels of total waste collected per capita (less than 0.0054 ton per inhabitant) in areas with a density lower than 73 inhabitants per km^2, involves an environmental cost of 541 Euros per ton. This cost could be lower, 327 Euros per ton, in regions with a population density greater than 73 inhabitants per km^2. Overall, the findings indicate that the lack of collecting and recycling waste in densely populated areas (regardless of its magnitude) could be associated with high levels of environmental cost. Therefore, it is of great importance for the municipalities to put efforts to improve the performance of collection and recycling services as this could bring huge economic and environmental benefits for the citizens and the environment.

As robustness check, we performed a linear regression where the shadow price of unsorted waste was used as the dependent variable and the set of environmental variables such as the amount of waste generated per capita, tourist index and population density were used as explanatory variables. The results are reported in Table 5. It is found that all environmental variables had a statistically significant impact on the shadow price of unsorted waste. Keeping other things fixed, a unit increase in population density could lead to an increase in the shadow price of unsorted waste by 0.475 units on average. If the collection and recycling of waste per capita increases by one unit, then the shadow price of unsorted waste could result in an increase by 0.107 units, keeping other factors the same. Therefore, on average the collection of more waste per capita in more densely populated areas could increase the implicit cost of dealing with unsorted waste. It is finally found that a unit increase in the tourist index could lead to a reduction in the shadow price of unsorted waste by 0.007 units on average, ceteris paribus. This means that more touristic areas might have more frequent waste services and drop off points for the collection of recyclable waste materials. Thus, on average these regions might experience lower levels of environmental cost for each ton of waste remained unsorted as consequence of collection waste activities.

The economic and environmental performance (eco-efficiency) of the assessed Chilean municipalities in the provision of MSW services has been identified as poor. Hence, within the circular economy framework, policies and actions to improve eco-efficiency of municipalities need to develop. Currently, in Chile, the municipalities are responsible of MSW management, which means that potential economies of scale are not exploited. The management of MSW at larger scale (e.g., metropolitan of regional level) might involve lower operational costs and therefore, improvements in eco-efficiency.

As it is shown in Table 1, the percentage of recycled MSW in the evaluated municipalities was only 3.8% which also explains the poor performance in the management of MSW. To improve the eco-efficiency of the municipalities it is relevant to increase the percentage of recyclable waste collected. In doing so, municipalities should develop MSW collection strategies adapted to the specific conditions and environment of the collection zone (e.g., population density, types of buildings), public acceptability and preferences of local people by the different

Table 5
Estimates from linear regression.

Variables	Coeff.	St. Err.	T-stat	p-value
Constant	2.936	1.605	***1.830***	0.067
Population density	0.475	0.064	**7.379**	0.000
Tourist index	−0.007	0.002	**−3.777**	0.000
Waste per inhabitant	0.107	0.018	**5.977**	0.000
R^2	0.53			
F-stat	141.1			
p-value	0.000			

Number of observations: 119.
Bold indicates that coefficients are statistically significant at 5% significance level.
Bold italic indicates that coefficients are statistically significant at 10% significance level.

collection methods. According to the European Commission (2022), who has proposed best practices in the waste management sector, door-to-door or curbside collection rounds from households, when appropriate within pay-as-you-throw systems are identified as best practices to collect MSW promoting its recycling. Other alternative methods for collecting recyclable materials could be implemented such as drop-off centers, buy-back centers, or deposit/refund programs. Each of these alternatives presents pros and cons and therefore, its adoption would depend on the preferences and socio-economic conditions of the local communities. For example, drop-off centers require public education and high participation to be effective. This system works best if there are positive incentives to encourage participation or negative ones to not participating. Deposit/refund programs also require participation and cooperation with local markets and packaging producers but are an excellent approach to reduce the generation of MSW.

Given the lack of experience of most of the Chilean municipalities in implementing MSW collection systems focused on recycling issues, they should develop pilot cases to investigate the environmental, social, economic and technical feasibility of different MSW collection methods in their local territories. Moreover, surveys to the local communities could also be carried out to better understand their preferences and therefore, selecting MSW collection systems fitting them.

5. Conclusions

Proper management of MSW requires the evaluation of its efficiency from an economic and environmental perspective. This is due to the fact that during the management of solid waste, several desirable products such as recyclable of paper, glass and plastic, and other undesirable products such as unsorted waste could be jointly produced. A unified analysis of the performance therefore requires the minimization of economic costs in conjunction with any undesirable products while collecting as much as desirable products as possible. Additionally, understanding how much it costs to contract undesirable products in solid waste sector could be of great significance to policy makers and citizens as it could boost environmental sustainability and promote the benefits of circular economy.

In this study, we used a mix of parametric and linear programming techniques to estimate the shadow price of unsorted waste in the Chilean MSW sector. This approach allows us to estimate the environmental costs avoided from dealing with any unsorted waste or equivalently, the environmental benefits obtained from removing these undesirable products from the waste process.

From a policy perspective, the findings of our study could be of great significance for several reasons. First, we provide a methodology that evaluates the eco-efficiency of the waste sector and displays the levels of efficiency across municipalities and regions. Thus, policy makers can identify the best and worst performers within the sector. Moreover, and most importantly, our methodology permits the quantification of the eco-benefits obtained from dealing with any undesirable products generated during the collection and recycling process. We note that this methodology can be used to identify the eco-efficiency of any sector in the economy such as water and energy. Moreover, the shadow price approach can be used to estimate the implicit cost of reducing the amount of any undesirable products such as carbon emissions or pollutants removals from the energy or wastewater treatment process. The inclusion of environmental variables in our analysis allows policy makers to understand how much economic and environmental costs could be affected when dealing with unsorted waste. It appears that the collection and recycling of large amounts of waste per capita in touristic regions could bring substantial environmental benefits. These factors should be included in business decision making process to the path toward environmental and economic sustainability while protecting the health of people and environment.

Despite the novelty of the methods applied and the results reported in this study, it is not exempt of limitations. First, eco-efficiency scores and shadow prices of unsorted waste were estimated using data for the year 2018 only. Hence, further research might involve assessing the performance of Chilean municipalities across years, i.e., evaluate changes in the eco-efficiency and shadow prices of unsorted waste over time. Second, the number of potential variables investigated as potential factors influencing the shadow price of unsorted waste was limited. Past research has revealed that other exogenous variables might influence the performance of waste service providers. This limitation have an effect on the potential use of the shadow prices estimates to define a tax to reduce the amount of unsorted waste. Hence, future research is required to extend the analysis conducted to assess the influence of environmental variables on the shadow price of unsorted waste.

Credit author statement

Ramón Sala-Garrido: Data Curation; Writing - Review & Editing. Manuel Mocholi-Arce: Formal analysis; Writing - Review & Editing. María Molinos-Senante: Conceptualization; Writing - Review & Editing. Alexandros Maziotis: Methodology; Software; Writing - Original Draft.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116668.

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