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Factors affecting eco-efficiency of municipal waste services in Tuscan municipalities: An empirical investigation of different management models

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ABSTRACT

The efficient provision of municipal solid waste (MSW) services is essential from an economic and environmental perspective. This paper investigates the effect of ownership type on the eco-efficiency of MSW management in Tuscan municipalities. In the first stage of the analysis, the authors use a data envelopment analysis metafrontier approach with the integration of unsorted waste as an undesirable output. Three different clusters of municipalities are created based on the ownership type of the municipal waste operators: public, private, and mixed. In the second stage of analysis, the paper investigates factors affecting eco-efficiency in order to provide new knowledge that can be used by policy and decision makers to improve eco-efficiency. The results show that eco-efficiency is higher for municipalities that entrust the delivery of waste services to publicly owned firms compared to municipalities with delivery by mixed and private firms. Moreover, eco-efficiency in MSW management is higher for municipalities with younger residents, a larger population, and an overall higher population density. Smaller municipalities and those with less tourism manage their waste services more eco-efficiently than do bigger municipalities and those with more tourism. The results indicate that policy-makers should improve communication and engagement activities with older residents in smaller, less densely populated areas. In municipalities featuring heavy tourism, eco-taxes could be used to support these activities, avoiding any impact on residents.

1. Introduction

Waste management includes the collection, transport, recovery, and disposal of waste. In recent years, the European Union (EU) has devoted considerable attention to waste management policies with the aim of increasing resource efficiency and reducing the negative impact of waste on the environment and citizens' health. The EU policies are focused on the reduction of waste generation and the growth of recycling activities. The EU's 7th Environment Action Programme states that European countries should reduce the amount of waste generated, maximize recycling and re-use, and limit incineration and landfilling to non-recyclable materials. Moreover, European directives set specific targets for recycling, requiring improvements in separate collection and the reduction of unsorted waste to be landfilled or incinerated.[1] Despite this, data on all economic activities and households from 2016 show that EU countries generated the highest amount of total waste since 2004 (Eurostat, 2018). Efficient management of municipal waste services is necessary in order to reduce costs, to provide better quality services, to reduce tariffs for citizens, and to fulfill the requirements outlined by the EU. Thus, it is necessary to improve eco-efficiency in the management of municipal solid waste (MSW).

Several studies have found that factors like income, gender, and age have an effect on the willingness to pay for environmental issues as well as on perceptions and practices regarding waste disposal (e.g., Song et al., 2012; Al-khateeb et al., 2017; ÓBrien and Thondhlana, 2019). Prior research has also found that environmental variables affect efficiency in the provision of MSW service (e.g., Carvalho et al., 2015; Sarra et al., 2017; Halkos and Petrou, 2019). Moreover, some scholars have investigated the link between the provider's ownership type (e.g., publicly owned or privately owned) for MSW services and their costs and efficiency results (Lombrano, 2009; Bel and Fageda, 2010; Simões et al., 2012; Pérez-López et al., 2016), showing diverging results (Simões and Marques, 2012). A meta-regression analysis of the existing

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[1] This is addressed in EU Directive 2018/851, which amended Directive 2008/98/EC.

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literature (Simões and Marques, 2012), however, appears to demonstrate that in the wealthiest countries the public provision of urban waste services is more effective and, over time, provides greater benefits than privatization.

Existing studies comparing the performance of MSW service providers have two ley limitations. First, most previous studies focus on cost efficiency assessment using the total cost of the service as input and tons of MSW collected as output. This approach ignores the environmental performance of the waste service providers since recyclables and unsorted waste are both considered outputs, despite the fact that they have significantly different impacts on the environment. Exceptions to this approach that consider both recyclables and unsorted waste in estimating the eco-efficiency of waste service providers include studies conducted by Díaz-Villavicencio et al. (2017), Sarra et al. (2017), Guerrini et al. (2017), Expósito and Velasco (2018), Agovino et al. (2018), Yang et al. (2018), and Halkos and Petrous (2019). Second, with the exception of Perez-Lopez et al., (2016), past research on this topic assumed that different types of waste service providers (i.e., *public* [owned by municipalities or publicly owned firms], *private*, or *mixed ownership* [having both private and public owners]) share the same production frontier. However, in other areas such as water utilities, research (e.g., Molinos-Senante and Sala-Garrido, 2016; Molinos-Senante et al., 2017) finds that ownership impacts the production frontiers of the units evaluated (MSW service providers in this study). Thus, the previous research is limited and inconclusive, warranting the need for further research with methods that take into account environmental targets (in this case, to reach higher rates of separate waste collection), updated information, and a focus on the municipal level where policies are formulated.

Using a 2016 database covering all municipalities in Tuscany, a region in the center of Italy, this paper contributes to the existing literature by proposing a novel approach to measuring the eco-efficiency of municipal waste management services. In this study, a data envelopment analysis (DEA) metafrontier approach is used. Perez-Lopez et al., (2016) previously used this approach in their study of the waste industry by accounting for an undesirable output (i.e., unsorted waste) along with a desirable output (i.e., separate waste collected) in accordance with European waste policies. Moreover, due to the existing debate about the pros and cons of contracting out public service management, this paper compares the eco-efficiency of three different clusters: municipalities with publicly owned, mixed ownership, and privately owned waste operators. Finally, existing studies of factors affecting eco-efficiency (such as population density, altitude, and income) are inconclusive (e.g., Passarini et al., 2011; Sarra et al., 2017); in order to guide managers and policy-makers in different contexts, this paper uses a two-stage analysis to identify factors that affect eco-efficiency in MSW management. The knowledge of these characteristics will be useful for the design of effective MSW policies.

The rest of this paper is organized as follows: the next section provides an overview of Italian and Tuscan MSW management. Then, sections three and four report the methods and data used in the empirical analysis, respectively. Section five reports the empirical results of the analysis, and section six provides the discussion and concluding remarks.

2. Italian and Tuscan municipal solid waste management

Italy recorded a relatively low quantity of waste generation per inhabitant and high recycling rates, with a significant increase in recycling rates over the last decade (European Environment Agency, 2016). There was some variation at the regional level: Tuscany recorded the second highest level of urban waste generation (616 kg/inh) and a separate collection rate lower than the national average (51.1% vs 52.8% at regional level) (Istat, 2018). Despite diverging results at regional and local levels, the overall trends of waste generation and recycling indicate a good opportunity to put EU policies into practice.

In 2018, the Italian government created the National Authority for Urban Waste Management (called ARERA) to implement a new framework with the aim of developing a nationwide method for tariff setting, which would include differentiation at the local level to accommodate variation in municipal policies and strategies. According to Istat (2018), 69.9% of Italian families think that urban waste tariffs are too high; this rate is higher in Tuscany, where 75.8% of families are unsatisfied with the cost of urban waste management services. This is directly linked to the need for reduced public spending driven by public financial constraints (Sarra et al., 2017; Simões and Marques, 2012) and to the full cost recovering principle, which requires that all of the operators' costs must be covered by tariffs paid by customers. For these reasons, eco-efficiency measurement and benchmarking are of utmost importance in urban waste management to avoid any unjustified tariff increases. Moreover, special attention should be given to environmental targets, such as unsorted waste reduction and increasing the recycling rate, as quality public service is costly (Picazo-Tadeo et al., 2008) and cost reduction should not endanger the fulfilment of environmental targets.

Urban waste services in Tuscan municipalities have different ownership and management models, from in-house provision to public-private partnerships to total privatization of the service. The privatization process has been substantial in Tuscany, with half of Tuscan municipalities with MSW operators having mixed or completely private ownership (Romano et al., 2019). Past research on MSW management in Italy did not find any effect of privatization on the costs of collection and transport of urban waste (Lombrano, 2009). Di Foggia and Beccarello (2018) analyzed the efficiency of the areas in which waste collection and disposal services are organized; their results showed heterogeneity across areas in Italy. With reference to Tuscany, Romano et al. (2019) found that ownership has an impact on waste production and the separate collection rate at the municipal level. With private operators, there was a higher production of waste and lower rates of separate collection compared to the services directly managed by municipalities or entrusted to publicly owned firms. Moreover, population density and the income of residents are relevant factors affecting the environmental performance of municipalities (Romano et al., 2019).

3. Methodology

3.1. Estimation of eco-efficiency scores

First, we present the fundamental assumptions required for evaluating and comparing the eco-efficiency of MSW operators according to their form of service provision (i.e., public, private, and mixed). Suppose that there are $K(>1)$ forms of MSW service provision with each operating under different group-specific technologies and using a vector of inputs, $x \in \Re_+^N$ to produce a vector of desirable outputs, $y^d \in \Re_+^M$, and undesirable outputs, $y^u \in \Re_+^L$. According to O'Donnell et al. (2008), the metafrontier is defined as a common boundary that envelopes every group-specific frontier. Hence, the metatechnology set (T^*), which contains all input-output combinations that are technologically feasible, is defined as follows (Lin et al., 2013):

$$T^* = \{ (x, y^d, y^u) : x \in \Re_+^N, y^d \in \Re_+^M, y^u \in \Re_+^L, x \text{ can produce } (y^d, y^u) \text{ in at least one group technology set, } T^k, k = 1, 2, \cdots, K \} \quad (1)$$

Let $P^*(x)$ be the possibility set, defined as the desirable feasible output set for the given input set $N^*(y^d, y^u)$ associated with the metafrontier technology set. According Choi et al. (2015), $P^*(x)$ can be elaborated by using the directional distance function, which is a generalization of the Shephard distance function that seeks to maximize the desirable output generation while simultaneously decreasing the undesirable output (Sala-Garrido et al., 2019). The directional meta-distance function is:

$$\overrightarrow{D^*}\left(x, y^d, y^u, \overrightarrow{g_{y^d}}, \overrightarrow{g_{y^u}}\right) = \max\left\{\beta : \left(y^d + \beta\overrightarrow{g_{y^d}}, y^u - \beta\overrightarrow{g_{y^u}}\right) \in P^*(x)\right\} \tag{2}$$

where $\vec{g} = (\overrightarrow{g_{y^d}}, \overrightarrow{g_{y^u}})$ is the vector describing the directions in which both desirable and undesirable outputs should be scaled. Following Chung et al. (1997), the direction vector selected in this study was $\vec{g} = (y^d, y^u)$, which requires that desirable outputs increase and undesirable outputs decrease.

According to Perez-Lopez et al. (2016), operators using different forms to provide MSW services are prevented from choosing from the full range of technologically feasible input-output combinations in the metatechnology set (T^*). By contrast, the input-output combinations available to waste service operators in the kth group are defined by the group-specific technology set defined as:

$$T^k = \left\{(x, y^d, y^u) : x \in N^k(y^d, y^u), (y^d, y^u) \in P^k(x), \right.$$
$$\left. x \text{ can be used by municipalities in group } k \text{ to produce } (y^d, y^u)\right\} \tag{3}$$

where $P^k(x)$ is the possibility set defined as the desirable feasible output set for the given input set $N^k(y^d, y^u)$ associated with the kth groups technology set.

Similar to the metafrontier technology set, the K group-specific technologies are represented by the following directional distance functions:

$$\overrightarrow{D^k}\left(x, y^d, y^u, \overrightarrow{g_{y^d}}, \overrightarrow{g_{y^u}}\right) = \max\left\{\beta : \left(y^d + \beta\overrightarrow{g_{y^d}}, y^u - \beta\overrightarrow{g_{y^u}}\right) \in P^k(x)\right\} \tag{4}$$

Following Kumar and Khanna (2009), the metafrontier eco-efficiency (E^*) (i.e., the eco-efficiency score with respect to the metafrontier) for the ith firm is defined as:

$$E_i^* = (1 + \overrightarrow{D^*}(x_i, y_i^d, y_i^u))/(1 + \overrightarrow{D^*}(x_i, y_i^d)) \tag{5}$$

Similar to E_i^*, the eco-efficiency with respect to the group-k frontier is defined as:

$$E_i^k = (1 + \overrightarrow{D^k}(x_i, y_i^d, y_i^u))/(1 + \overrightarrow{D^k}(x_i, y_i^d)) \tag{6}$$

Both E_i^* and E_i^k take values less than or equal to one. $E_i^* = 1$ and $E_i^k = 1$ indicate that the ith operator is eco-efficient with respect to the metafrontier and the group-k frontier, respectively. By contrast, $(1 - E_i^*)$ and $\left(1 - E_i^k\right)$ represent the input savings potential of the ith operator in comparison with the peers located on the metafrontier and group-k frontier, respectively. According to the definition of the metatechnology, $T^* = \left\{T^1 \cup T^2 \cup \cdots \cup T^k\right\}, \ k = 1, 2, \cdots K$, the eco-efficiency for each group (E^k) cannot be smaller than the eco-efficiency with respect to the metafrontier (E^*) (Molinos-Senante and Sala-Garrido, 2016).

Following Battese et al. (2004), O'Donnell et al. (2008) defined the metatechnology ratio (MTR) as the ratio of eco-efficiency with respect to the metafrontier and the technologies of different groups. It represents the distance between the technology of group-k and the metatechnology, as shown in Eq. (7).

$$MTR_i^k = \frac{E_i^*}{E_i^k} \tag{7}$$

As shown in Eq. (7), the measurement of eco-efficiency related to the metafrontier can be decomposed into two components: (i) the distance from an input/output point to the group-k frontier; and (ii) the distance between the group-k frontier and the metafrontier, representing the restrictive nature of the production environment.

Directional distance functions must be estimated to compute E_i^* and E_i^k. To do this, there are two main approaches: parametric and non-parametric methods. On the one hand, parametric methods such as stochastic frontier analysis (SFA) allow for the accommodation of errors of approximation and other sources of statistical noise (Huang et al., 2015). In contrast to SFA, the DEA technique is a non-parametric method and does not require any explicit definition of the specific mathematical form of the directional distance function. Moreover, DEA is an extreme point method comparing each producer with the best producer (Yu et al., 2018). DEA is a linear programming technique that envelops all input-output combinations with a piecewise linear frontier that sets the benchmark against which the units (i.e., MSW service operators) are evaluated. Thus, in this study, the directional distance functions were calculated by solving the following linear programming model:

$$\begin{aligned}
&\vec{D}^d(x_i, y_i^d, y_i^u) = \max \beta \\
&\qquad \textit{subject to} \\
&\textstyle\sum_{i=1 i\neq k}^{K} \lambda_i Y_i^d \geq (1 + \beta) \cdot y_k^d \\
&\textstyle\sum_{i=1 i\neq k}^{K} \lambda_i Y_i^u = (1 - \beta) \cdot y_k^u \\
&\quad \textstyle\sum_{i=1 i\neq k}^{K} \lambda_i X_i \leq x_k \\
&\qquad \lambda_i \geq 0, \forall i
\end{aligned} \tag{8}$$

where the superscript d in the objective function represents various types of directional distance functions (i.e., $\overrightarrow{D^k}$ and $\overrightarrow{D^*}$); Y^d, Y^u, and X represent an $(M \times K)$ matrix of the desirable outputs, a $(L \times K)$ matrix of undesirable outputs, and an $(N \times K)$ matrix of inputs, respectively; λ_i is the intensity variable used to construct the production possibility set through a convex combination of units.[2]

3.2. Identification of determinants of eco-efficiency

To investigate the determinants of eco-efficiency in the provision of MSW services, we conducted a second analysis. In this analysis, several methodological approaches can be employed, and regression analysis is one of the most common approaches (D'Inverno et al., 2018). However, this technique suffers important methodological shortcomings (Badin et al., 2014). First, there is model misspecification since the explanatory variables should have been considered in the first DEA stage (Molinos-Senante et al., 2016). Second, biased results might arise from serial correlation between the error term and the covariates in the second stage (Simar and Wilson, 2007).

In line with the growing literature, we identified factors affecting the eco-efficiency of waste service operators using a hypothesis test approach. First, waste service operators were grouped based on certain exogenous variables (see data section) that could affect their eco-efficiency. Second, a hypothesis test was conducted to evaluate whether or not there were statistically significant differences among groups of waste service operators according to the variable under scrutiny. Eco-efficiency scores computed in the first

[2] Readers interested in this methodological approach can consult the studies by Chen and Song (2008) and Tiedemann et al. (2011).

stage of analysis do not meet the homoscedasticity and normality assumptions. Hence, following previous studies (Hernández-Sancho et al., 2011; Dong et al., 2017), the Mann-Whitney U and Kruskal-Wallis non-parametric tests were applied to test the hypotheses. The null hypothesis (H_0) states that the groups originate from the same populations. H_0 can be rejected with a 95% level of significance if the p-value is equal to or less than 0.05, which means that differences in eco-efficiency scores among the groups of waste service operators are statistically significant.

4. Sample and data description

The empirical analyses in this study involve all of the Tuscan municipalities for which all of the variables in the model are available; this includes 225 of the 279 municipalities in Italy's Tuscany Region. Forty-five municipalities were excluded due to the lack of data about costs for managing the urban waste management service in the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) dataset. Another nine municipalities were excluded due to the lack of data on one or more of the other variables in the empirical analysis. These 225 municipalities contain 87.5% of the regional population.

Given our aim of analyzing eco-efficiency in MSW services, we collected data in 2016 on the names of waste operators entrusted with urban waste management activities and classified them based on their ownership type. In 117 of the 225 municipalities (52%), the waste operators were publicly owned firms; in 92 municipalities (41%), the waste operators were mixed-owned firms; and the remaining 16 municipalities (7%) employed privately owned operators.

Following previous studies on the efficiency of waste service management (Boetti et al., 2012; Guerrini et al., 2017; Marques and Simoes, 2009; Rogge and De Jaeger, 2013; Sarra et al., 2017; Simões et al., 2010, Simões et al., 2012; Worthington and Dollery, 2001), cost variables were included as inputs. Data about costs at the municipal level in 2016 have been collected from the ISPRA dataset available on its website.[3] In particular, three inputs were considered: (i) total cost of unsorted waste (euros/year); (ii) total cost of recyclables (euros/year); and (iii) other costs (euros/year). *Total cost* included costs for collection and transport of unsorted waste, for treatment and disposal of unsorted waste, for collection and transport of sorted recyclable waste, and for treatment and recycling of sorted recyclable waste. Other costs included street sweeping and washing; shared costs (administrative, collection and litigation, general management, other); and costs of capital (amortization of the mechanical means for the collection, sweeping means and tools, containers for collection, financial depreciation for transferable assets and others, provisions and remuneration of capital).

The amount of waste collected has been used in many prior empirical studies as an output (Boetti et al., 2012; Bosch et al., 2000; García-Sánchez, 2008; Guerrini et al., 2017; Marques and Simoes, 2009; Rogge and De Jaeger, 2013; Sarra et al., 2017). We collected data from ISPRA about recyclables (tons/year) and unsorted waste (tons/year) collected in each municipality in 2016. These measures were integrated in the eco-efficiency assessment as desirable outputs (i.e., recyclables) and undesirable outputs (i.e., unsorted waste). In accordance with the European framework and national legislation, Italian municipalities should fulfill recycling targets. Since 2008, the European Union legislative framework, with the Directive 2008/98/EC (EU 2008, DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives), required separate waste collection for paper, metal, plastic, and glass by 2015 in order to prepare waste for re-use, recycling, or other recovery operations. The Italian regulation set specific minimum targets for separate collection and offered incentives, such as a tariff reduction, for exceeding the fixed thresholds. We include recyclables as a desirable output and unsorted waste as an undesirable output, given that municipalities should increase the former and reduce the latter to comply with regulatory targets and sustainability goals.

In selecting the potential exogenous variables affecting eco-efficiency scores, we took into account the features of the MSW sector, the available data for Tuscan municipalities, and the extant literature (e.g., Guerrini et al., 2017; Sarra et al., 2017; Expósito and Velasco, 2018; Calabrò and Komilis, 2019). The 225 municipalities were classified into groups according to the average values of each exogenous variable (see Table 1). For example, given that the average income per capita of the 225 municipalities evaluated is 13,941 €/year, the Tuscan municipalities were grouped into three clusters: (i) less than 13,000 €/year, (ii) between 13,000 and 15,000 €/year, and (iii) more than 15,000 €/year. No consensus has been reached in the extant literature on the impact that these exogenous and environmental variables have on efficiency levels; thus, further research is needed to clarify this issue:

(i) The average *income per capita* of the population served by the MSW operator is expressed in €/year. Prior research on the influence of income per capita on efficiency in the provision of MSW services is ambiguous. On the one hand, some studies (e.g., Sarra et al., 2017; Expósito and Velasco, 2018) illustrate that larger per capita incomes are associated with higher levels of separate collection and, therefore, greater efficiency of firms. By contrast, Benito et al. (2011) concluded that large per capita income does not promote efficiency because larger amounts of taxes can be collected to cover the costs of inefficiency. With reference to Tuscany, Romano et al. (2019) showed that higher average taxable income decreases municipal waste production and increases the separate collection rate, thereby improving environmental performance. Finally, Tsalis et al. (2018) showed that the income level did not affect recycling frequency.

(ii) The average *age* of the population served by the MSW operator is the second explanatory variable. Soukopová et al. (2017) evaluated the effects of aging on the cost of municipal waste collection. They demonstrated that senior citizens have a significant influence on the production of municipal waste and on the expenditure devoted to dealing with it. Recently, Tsalis et al. (2018) showed that the age of respondents influenced their recycling behavior, with older people being more willing to comply with regulations. In a different vein, Calabrò and Komilis (2019) found that recycling behavior was not linked to age. Thus, further research is needed on this matter. To evaluate the impact of average age of the population on municipalitieś eco-efficiency and based on the average age of the people from the municipalities evaluated,two groups were considered: (i) younger than 47 years old and (ii) older than 47 years old.

(iii) *Male* ratio is defined as the percentage of males in the population served by the MSW operator. The impact of gender on waste production was investigated by Talalaj and Walery (2015), who found that a greater femalpo-e-to-male ratio leads to a higher rate of waste generation. Further, the linkage between gender and both attitudes and practices related to street littering was investigated by Al-Khatib et al. (2009), who found that men and women think about and respond differently to environmental issues. However, other studies found no significant relationship between recycling behavior and gender (Gamba and Oskamp, 1994; Werner and Makela, 1998; Calabrò and Komilis, 2019) or between waste generated and gender (Chamizo-Gonzalez et al., 2016). Municipalities were clustered into two groups: (i) ratio of males lower than

[3] Interested readers can consult detailed data at www.isprambiente.gov.it/.

Table 1
Statistical information to estimate eco-efficiency of Tuscan waste operators.

Type of MSW provider		Average				Standard deviation			
		Public	Mixed	Private	Total	Public	Mixed	Private	Total
Inputs (Euros/year)	Total costs unsorted waste	1,339,907	452,261	359,375	907,231	2,981,556	657,819	605,282	2,237,890
	Total costs recyclables	1,204,671	295,887	231,023	763,842	1,982,295	580,175	205,693	1,544,738
	Other costs	1,864,885	1,015,558	489,652	1,419,810	4,627,993	1,666,504	746,148	3,534,055
Undesirable output (ton/year)	Unsorted waste	5914	2713	1352	4280	14,448	4057	2630	10,875
Desirable output (ton/year)	Recyclable waste	7028	2263	1332	4674	14,092	4845	1554	10,890
Exogenous variables	Average income (Euros/year)	14,329	13,577	13,207	13,941	1912	1639	797	1789
	Average age (years)	46.29	47.52	49.41	47.01	2.20	2.38	3.80	2.55
	%Male	49.0	49.1	48.8	49.0	1.0	1.3	1.3	1.2
	Population (inhabitants)	20,823	8211	5296	14,562	43,330	13,075	5159	32,965
	Size (km^2)	59.69	107.69	63.70	79.60	44.06	79.07	52.45	64.41
	Population density (inh/km^2)	382	90	217	251	510	112	342	409
	Tourists ratio	9.7	16.7	19.8	14.8	20.7	20.9	76.4	36.5

50%, which means that most people are female; and (ii) ratio of males larger than 50%, which indicates that most people are male.

(iv) *Population served* is defined as the number of inhabitants to whom the waste operator provides MSW service. With reference to this variable, Agovino et al. (2016) and Guerrini et al. (2017) showed that smaller municipalities tend to have a more favorable operational environment for efficiency. Other studies, by contrast, demonstrated increasing returns to scale (Carvalho and Marques, 2014; Vishwakarma et al., 2012; Worthington and Dollery, 2002) or showed no effect of size (García-Sánchez, 2008). As highlighted by Guerrini et al. (2017) for the Veneto region in the northern part of Italy, differences in empirical results could be due to characteristics of the dataset and, more generally, to the Italian context, which has mainly small municipalities. The municipalities evaluated were categorized into three groups based on population: (i) fewer than 4000 inhabitants; (ii) between 4000 and 10,000 inhabitants; and (iii) more than 10,000 inhabitants.

(v) The *size* of the municipality in which the operator provides MSW service is expressed in km^2. In Tuscany, size varies significantly among municipalities: there are municipalities with areas larger than 470 km^2, and there are municipalities with areas larger than 10 km^2. In other Italian regions, size has been found to influence both the operational complexity of the service and its costs significantly; moreover, control over how separate collection is performed by citizens becomes more difficult in larger areas (Sarra et al., 2017). To examine the influence of the size of the municipality on the eco-efficiency of MSW service provision, three groups were formed: (i) less than 50 km^2; (ii) between 50 and 100 km^2; and (iii) more than 100 km^2.

(vi) *Population density* is expressed as the number of people per km^2. Like municipal size, population density varies significantly among Italian and Tuscan municipalities. In Tuscany, some municipalities have a population density lower than 10 inhabitants per km^2, and others have a population density of more than 3700 people per km^2. An analysis of the literature on the impact of this variable on efficiency and environmental performance (Guerrini et al., 2017) highlighted the need for further research. While some studies that found that higher population density causes lower costs because more waste is collected at each pickup point (Callan and Thomas, 2001; Carroll, 1995; Dubin and Navarro, 1988; Koushki et al., 2004), other studies showed that higher density reduced efficiency (Benito et al., 2010, 2011; De Jaeger et al., 2011; Vishwakarma et al., 2012; Worthington and Dollery, 2001) because large equipment could not be used in narrow and densely populated streets. To evaluate the effect of population density on the eco-efficiency of Tuscan firms, the firms were classified into three groups, taking into account that the minimum and maximum population density of the municipalities evaluated are 6.9 and 3,741 people/km^2, respectively: (i) fewer than 50 people/km^2; (ii) between 50 and 200 people/km^2; and (iii) more than 200 people/km^2.

(vii) *Tourism* is the ratio between the annual number of tourists received by the municipality and the number of permanent inhabitants of the municipality.

According to prior literature, tourism may affect eco-efficiency due to the marked increase in MSW generation as the seasonal population of tourists rises (Shamshiry et al., 2011; Mateu-Sbert et al., 2013). This variable was included in previous investigations with inconclusive results (Bosch et al., 2000; García-Sánchez, 2008; Sarra et al., 2017; Guerrini et al., 2017). In the case of Tuscan municipalities, tourism is an important variable, since more than 75% of regional firms operate in areas where 34% are in service trades, transport, and hotel industries (European Union, 2019). Moreover, 69.5% of the employment in Tuscany is concentrated in the service sector (European Union, 2019). Based on the analysis of tourism in Tuscany, three groups of municipalities were formed: (i) fewer than two tourists per inhabitant; (ii) between two and 10 tourists per inhabitant; and (iii) more than 10 tourists per inhabitant.

Data from the website of the National Institute of Statistics (ISTAT) was used for the measurement of the exogenous variables.[4] The dataset for the Tuscany Region was used to collect data about the touristic presence in each municipality, measured as the number of nights spent by tourists in hotels and other tourist accommodations.[5] Finally, information about the operators of the urban waste management services for each municipality was collected using the official websites for the municipalities and waste operators, the AIDA Database (Bureau Van Dijk), and direct contact with municipalities or local waste authorities (called ATO). The data were then crosschecked with the support of the Tuscan regional agency, Agenzia Regionale Recupero Risorse S.p.a. (ARRR), and ATO Costa data.

The means and standard deviations of the variables used to estimate the eco-efficiency of MSW providers in Tuscan municipalities and of the exogenous variables affecting eco-efficiency scores are shown in Table 1.

5. Results

5.1. Eco-efficiency scores

The basic premise for using the metafrontier concept in this study to evaluate the eco-efficiency of municipalities in the provision of MSW services is that the three categories (i.e., public, private, and mixed operators) entrusted by municipalities to

[4] Interested readers can consult detailed data at: www.comuni-italiani.it.

[5] Interested readers can consult detailed data at: www.regione.toscana.it/statistiche/dati-statistici/turismo.

provide the MSW services do not share a common technological frontier. In order to test this hypothesis, the Kruskal-Wallis test, which is non-parametric, was employed due to the non-normal distribution of the inputs and outputs. The null hypothesis (H_0) is that the three MSW service delivery forms operate under the same production frontier. If the *p*-value of the test is less than or equal to 0.05, the null hypothesis can be rejected with a 95% level of significance (Kruskal and Wallis, 1952). This means that waste service operators with different ownership are non-homogeneous regarding their technological frontier and, therefore, the metafrontier is required to compare the eco-efficiency among them. The results of the Kruskal-Wallis tests are shown in Table 2 and illustrate that for the five variables analyzed ($x_1, x_2, x_3, y_1^d, y_1^u$), the *p*-values are lower than 0.05. This finding supports the use of the DEA metafrontier approach to compare the eco-efficiency of waste service operators with different ownership.

The eco-efficiency scores obtained with respect to the group-*k* frontiers and their characteristics are shown in Figs. 1–3. The mean eco-efficiency values for municipalities with public, private, and mixed ownership of the providers of municipal waste services are 0.703, 0.972, and 0.668, respectively. The large average eco-efficiency and low deviation of values of municipalities with private waste service operators should be highlighted (Fig. 1). The results demonstrate that the 16 municipalities with private municipal waste service providers are homogeneous in terms of performance. By contrast, the eco-efficiency for mixed and public municipal services is heterogeneous, revealing marked differences across municipalities. The DEA approach also allows for the computation of the potential input savings (costs) if the municipal services were operated at their efficient group-*k* frontiers.

Based on the average eco-efficiency scores calculated (Table 3 and Fig. 2), municipalities with public, private, and mixed providers of municipal waste services could potentially save 29.7%, 2.8% and 33.2% of their current costs, respectively. From a management perspective, this means that almost all municipalities with private firms as operators have the same performance as the best performing municipality. By contrast, municipalities with public and mixed firms have notable room to save costs while keeping the production of both desirable and undesirable outputs constant.

In evaluating the performance of municipalities, it is also relevant to analyze the percentage of efficient municipalities in the population (i.e., the municipalities that have the best performance). Table 3 illustrates that 75% of the municipalities with private providers of municipal waste services (12 out of 16) are eco-efficient (i.e., they are located on the efficient frontier and, therefore, they have the best performance among their technological group). By contrast, only 21.4% of the public firms (25 out of 117) and 19.6% of mixed firms (18 out of 92) are eco-efficient. Thus, 78.6% and 80.4% of municipalities with public and mixed firms, respectively, could save costs if they operated as efficiently as the most efficient municipalities in the analysis. This finding confirms that municipalities with public and mixed ownership are more heterogeneous in terms of performance when compared to the municipalities with private waste operators.

To compare performance among municipalities with public, private, and mixed firms as providers of municipal waste services, eco-efficiency scores with respect to the metafrontier were computed. In line with our theoretical expectations, Fig. 2 shows that eco-efficiency scores computed based on the metafrontier (E^*) are smaller than those computed with respect to the individual frontiers (E^k). Unlike when eco-efficiency was estimated with respect to group-*k* frontiers, Fig. 2 shows that the average eco-efficiency scores relative to the metafrontier of the three types of municipalities are similar. The lowest average eco-efficiency corresponds to municipalities with mixed waste operators, whereas the largest corresponds to public operators. The results suggest that municipalities with mixed ownership providers of MSW services exhibited the worst performance and municipalities with public providers exhibited the best performance. This finding is supported by the percentage of eco-efficient municipalities in each group. Thus, only 5.4% of municipalities with mixed firms (5 out of 92) are eco-efficient, whereas 20.5% of municipalities with public firms (24 out of 117) are located on the metafrontier (i.e., are eco-efficient). Moreover, it should be noted that when eco-efficiency was estimated using the metafrontier as the reference, the number of eco-efficient municipalities with public waste operators remained almost constant since it only decreased from 21.4% to 20.5%. By contrast, for municipalities with private firms, this was

Table 2
Kruskal-Wallis test statistics for differences in the three clusters of MSW service operators.

	Costs unsorted waste	Costs recyclable waste	Other costs	Unsorted waste	Recyclable waste
***p*-value**	<0.001	<0.001	0.041	0.002	<0.001

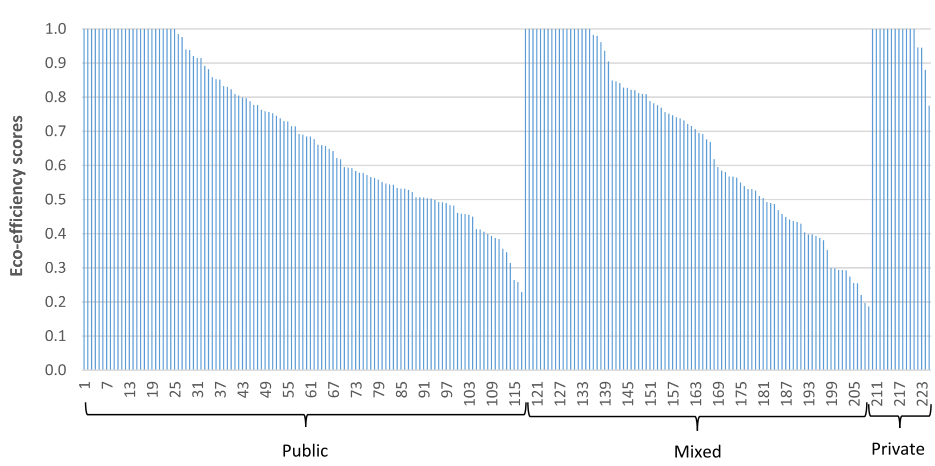

Fig. 1. Eco-efficiency scores (E^k) for public, mixed, and private waste service operators.

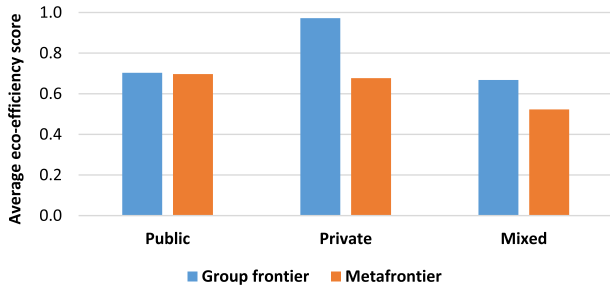

Fig. 2. Average efficiency scores with respect to group frontiers and to the metafrontier for public, private, and mixed municipal solid waste service operators.

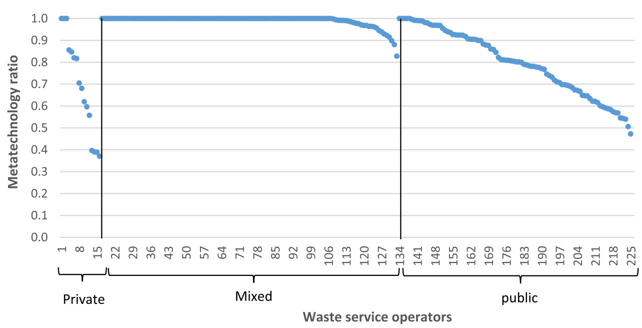

Fig. 3. Metatechnology ratio for private, mixed, and public waste service operators.

reduced from 75.0% to 18.8% (Table 3). This finding means that municipalities with private firms exhibit strong performance when they are compared to other private firms, but they have large room for improvement when compared to municipalities with different ownership types (i.e., public and mixed management models).

Since there is a low number of municipalities with private operators, eco-efficiency scores have also been estimated using only two clusters of municipalities: i) public and ii) non-public, which combines both mixed and private waste service operators. A summary of the results is shown in the Appendix. The results show both that the average eco-efficiency score of public waste service operators remained almost constant (0.703 vs. 0.754) and that the percentage of eco-efficient municipalities remained the same. Regarding the average eco-efficiency score for non-public operators (mixed and private), as expected, the score fell between the previous scores for private and mixed operators.

To analyze the distance between group-k frontiers and the metafrontier, the MTR for each waste service operator was evaluated (Fig. 3). According to Liu et al. (2017), an MTR equal to one means that the group-k frontier and the metafrontier match and, therefore, the firm has the minimum feasible input, given the output (desirable and undesirable) vectors. Table 3 shows that the average MTR for municipalities with public firms is 0.990, and for 91 out of 117 municipalities with public firms (see Fig. 3), MTR equals one. This indicates that the efficient frontier of municipalities with public firms is almost the same as the metafrontier. By contrast, the average MTR of municipalities with private firms is 0.690, and the MTR is one for only 3 out of 16 firms. Hence, the efficient frontier of the municipalities with private firms is far away from the metafrontier, which means that this group of municipalities has more room to improve their performance compared to municipalities with public firms.

5.2. Determinants of eco-efficiency

Once the eco-efficiency of municipalities with public, private, and mixed MSW operators was compared using the metafrontier approach, the exogenous variables were explored as potential determinants of the eco-efficiency scores. Table 4 shows the Mann-Whitney U and Kruskal-Wallis test results, the main statistics of eco-efficiency scores, and the percentage of efficient MSW services for each group of municipalities according to the seven exogenous variables described. The results in Table 4 illustrate that municipalities with a larger income per capita are the most eco-efficient in the provision of MSW services. However, the Kruskal-Wallis test results do not allow for the rejection of the null hypothesis, which indicates that the average income per capita is not a determinant factor for Tuscan municipalitieś eco-efficiency, thus confirming previous results (Benito et al., 2011; Expósito and Velasco, 2018; Romano et al., 2019; Sarra et al., 2017).

The differences between the two groups of the population (younger and older than 47 years of age) were statistically significant, showing that municipalities with a younger population are more eco-efficient in managing MSW services. This result suggests that municipalities should consider developing educational campaigns and engagement activities to raise awareness among older people about the importance of waste separation, promoting recycling, and the circular economy. Hence, our findings for Tuscan municipalities are consistent with the conclusions of Soukopová et al. (2017), who demonstrated that age influences waste production and management costs. This finding is in stark contrast with Tsalis et al. (2018), who found that older people are more willing to comply with regulations.

The last demographic variable evaluated was gender, defined as the ratio of males in the population. Municipalities were clustered into two groups: those with a ratio of males lower than 50% and those with a ratio larger than 50%, indicating that in each group most people are female or male, respectively. The results in Table 4 show that the average eco-efficiency scores of both groups of municipalities are very similar and, according the Mann-Whitney U test, the differences are not statistically significant. Hence, in Tuscan municipalities, gender is not an important predictor of eco-efficiency in the provision of MSW service.

The presence of economies of scale in the provision of MSW service has previously been investigated (e.g., Sarra et al., 2017; Pérez-López et al., 2018). Hence, in this study, the population served by the firm was analyzed as a potential determinant of eco-efficiency. The results shown in Table 4 demonstrate a statistically significant difference between large and small municipalities. Municipalities with large populations are the most eco-efficient in managing MSW services, whereas municipalities with small populations are the least efficient. Moreover, it was found that only 5.6% of the smaller municipalities are eco-efficient compared to 16.7% of the larger municipalities. These results reveal the presence of economies of scale in the provision of MSW service,

Table 3
Main statistics regarding eco-efficiency scores with respect to group frontiers and to the metafrontier for public, private, and mixed municipal solid waste service operators.

	Eco-efficiency with respect to group frontiers				Eco-efficiency with respect to the metafrontier				Metatechnology ratio (MTR)		
	Average	Std. Dev.	Min	% Efficient	Average	Std. Dev.	Min	% Efficient	Average	Std. Dev.	Min
Public	0.703	0.222	0.229	21.4	0.697	0.225	0.229	20.5	0.990	0.026	0.828
Private	0.972	0.062	0.775	75.0	0.677	0.240	0.303	18.8	0.690	0.227	0.371
Mixed	0.668	0.252	0.187	19.6	0.523	0.214	0.137	5.4	0.797	0.147	0.473

Table 4
Average eco-efficiency scores for waste service operators according potential determinants of efficiency and Kruskal-Wallis test results.

Exogenous variable	Number of firms	% efficient	Average	Std. Dev.	Min	Test
Income (€/year)						
<13,000	55	16.4	0.597	0.253	0.195	0.195
13,000–15,000	121	10.7	0.618	0.232	0.176	
>15,000	49	20.4	0.669	0.222	0.229	
Age (years)						
<47	127	17.3	0.674	0.212	0.224	<0.001
≥47	98	10.2	0.559	0.251	0.137	
Male (%)						
<50	197	15.7	0.626	0.237	0.136	0.791
≥50	28	3.6	0.611	0.227	0.176	
Population served (inhabitants)						
<4,000	82	5.6	0.590	0.226	0.195	0.039
4,000–10,000	66	13.4	0.602	0.250	0.177	
>10,000	77	16.7	0.676	0.223	0.137	
Municipality size (km^2)						
<50	91	16.5	0.686	0.222	0.176	<0.001
50–100	76	17.1	0.629	0.241	0.206	
≥100	58	6.9	0.522	0.221	0.137	
Population density (inhabitants/km^2)						
<50	73	13.7	0.590	0.255	0.195	<0.001
50–200	77	9.6	0.566	0.222	0.137	
≥200	79	19.0	0.710	0.207	0.236	
Tourism (tourist/inhabitants)						
<2	59	35.6	0.673	0.237	0.177	0.047
2–10	91	17.6	0.618	0.230	0.195	
≥10	75	24	0.578	0.235	0.137	

supporting the findings of a number of prior studies (Pérez-López et al., 2018; Carvalho and Marques, 2014; Vishwakarma et al., 2012). However, the present findings also contrast with prior research. For example, Expósito and Velasco (2018) concluded that the size of the served population does not explain the level of efficiency in the delivery of MSW services reached by Spanish regions, whereas Guerrini et al. (2017), in their sample of municipalities in the Verona region of Italy, found that smaller municipalities tended to have a more favorable operational environment. The mean population of the sample evaluated by Guerrini et al. (2017) was 7599 inhabitants, while the mean value in this study was 14,562 inhabitants; moreover, in the Tuscan dataset, only 49 out of 225 municipalities (21%) have more than 15,000 inhabitants. Thus, despite their similar focuses on Italian municipalities, the datasets used in each study are quite different, which may contribute to the variation in results.

Regarding the influence of the size of the municipality in km^2 on eco-efficiency, the results showed that the mean eco-efficiency score was greater for smaller municipalities than for larger ones. The Kruskal-Wallis test led us to reject the hypothesis of equality of means for eco-efficiency with 95% significance based on the three ranges. This supports the conclusion reached by Fidelis and Colmenero (2018) that the collection area had a positive impact on the performance of cooperatives in the management of MSW that can be recycled. Similar conclusions were reported by Sarra et al. (2017), whose DEA second stage analysis identified the area of the municipality as a significant variable with a negative sign. This means that, from a statistical point of view, as the size of the municipality increases, the efficiency of the waste service provision decreases.

The *p*-value of the Kruskal-Wallis test (<0.001) shows that population density has a significant effect on the eco-efficiency of waste service operators. Table 4 shows that municipalities with a large population density (>200 people/km^2) are the most eco-efficient. By contrast, for municipalities with small and moderate population densities, the average eco-efficiency scores of firms are similar. Previous studies are inconclusive about the effect of population density on urban waste collection costs (e.g., Koushki et al., 2004; Marques and Simoes, 2009; De Jaeger et al., 2011; Vishwakarma et al., 2012; Expósito and Velasco, 2018). Nevertheless, the findings of our study are partially consistent with Guerrini et al. (2017), who identified population densities between 200 and 250 and around 50 people/km^2 as unfavorable situations for efficiency.

The results reveal that municipalities with the lowest amount of tourism have the greatest eco-efficiency. In the Kruskal-Wallis test, the eco-efficiency differences for the three groups are statistically significant. This finding indicates that increased tourism negatively affects the eco-efficiency of municipalities, supporting the hypothesis of Bosch et al. (2000) and García-Sánchez, (2008) and the conclusion of Guerrini et al. (2017) that excess MSW produced during the peak tourist season is not collected efficiently.

6. Discussion

The empirical analysis shows that, when environmental targets are accounted for, Tuscan municipalities with publicly owned waste operators are more eco-efficient in MSW service provision. This result could be due to the fact that publicly owned firms are more directly linked with municipalities and their political representatives and, thus, are indirectly linked with citizens and their needs. For this reason, the strategies and policies of such firms are more prone to encompass not only economic and financial targets but also social and environmental goals, in a triple bottom-line approach (Elkington, 1998). Publicly owned operators are better able to engage citizens in separate waste collection and waste reduction (Romano et al., 2019). This fact could also be linked to their higher willingness to accept lower returns in terms of payout, for example, to strengthen the capability to meet environmental targets (in Italy, at least 65% of separate waste must be collected of the total amount of waste generated). In fact, if a municipality does not meet the separate waste collection targets, penalties are first applied to the municipality itself and then paid by citizens in the form of higher local taxes. Municipalities and the politicians who represent them are less willing to accept penalties to maintain and foster political support than private managers and owners; additionally, their ability to regulate publicly owned firms is much greater than their ability to regulate privately owned firms. In case of delegated management of the urban waste service to mixed or private operators, definitions of clear penalties for firms unable to meet the environmental targets that overcome the penalties applied for municipalities are necessary. Moreover, including environmental targets and ad hoc engagement and communication activities could be of utmost importance.

This empirical study also provides policy-makers with relevant insights to develop more eco-efficient MSW service. First, economies of scale exist owing to the fact that some costs for waste management are fixed (e.g., governance, administrative, financial, and research and development). Thus, municipalities with more inhabitants are better able to provide an eco-efficient waste service to their citizens because they can spread their fixed costs over a larger number of customers. This means that small municipalities should consider opportunities to increase the number of citizens served, for example, by merging the provision for two or more neighboring municipalities. However, policy-makers must also be aware that smaller municipalities in terms of the size of the territory served and municipalities with higher population density are more eco-efficient in providing MSW services. This result indicates that, along with economies of scale, economies of density also exist. Thus, merging waste services with other municipalities to achieve economies of scale could potentially be counterbalanced by the negative effects of serving a larger area that is less densely populated. For this reason, defining the optimal area for efficient management of MSW services should performed carefully with consideration of the concurrent effects of the size of the population, the size of the area served, and the population density.

Another factor that provides relevant insights for policy-makers is the average age of residents. The findings show that municipalities with older inhabitants have less efficiently managed MSW services. This result could be because older citizens are less keen to accept environmental innovation in waste management, such as separate waste collection. Thus, to maintain political support, policy- makers avoid imposing pro-environmental behaviors upon citizens and firms through either direct or delegated management. This finding should encourage municipalities to invest more in education campaigns to educate older populations to separate waste at home and to provide them with better explanations of the environmental targets to be met and their relevance for future generations. Moreover, older people may have greater difficulty in understanding how to differentiate waste, as this method was not used in the past, and it can be more difficult to change habits for older individuals. For this reason, information campaigns to support a better understanding of separating rules and providing incentives, such as tariff reduction, could be effective to realize this change. Additional policies to support older citizens, such as creating recycling drop-off stations with the presence of municipality employees to guide elder citizens on how to differentiate their waste, may also help increase efficiency.

The last factor affecting eco-efficiency in MSW service provision is the presence of tourists. Municipalities with more tourists obtain lower eco-efficiency in managing MSW services. Tourists often remain in a destination for less than a week, and it might be challenging or impossible for them to understand local differentiation rules for separate collection and to know the timetable for curbside collection. Thus, in tourist areas, the creation of recycling drop-offs and the provision of well-structured information material through advertising campaigns may be necessary to facilitate tourists' compliance with the waste policies adopted in these municipalities. Tourists' engagement should be supported by the providers of accommodations. Hotels and bed-and-breakfasts typically do not provide bins for separate collection. In addition to a new policy for increasing the knowledge of environmental targets and for promoting pro-environmental behaviors in municipalities with more tourism, it is of the utmost importance to introduce eco-taxes for tourists, which can be used to support stakeholders' engagement programs and to avoid penalties on residents for non-compliance.

7. Conclusions

MSW services are a key public service provided at the municipal level. Efficiently managing the provision of such services leads to cost savings, which can be channeled for tariff reductions or to improve the quantity and quality of services and, thus, citizens' well-being and environmental sustainability. The evaluation of efficiency of MSW services should not only focus on economic issues but also take into account environmental targets defined at the European, national, and local levels. Thus, in this study, we evaluated the eco-efficiency of a sample of waste service operators accounting for desirable outputs (i.e., separate waste collected) and undesirable outputs (i.e., unsorted waste collected). By using the DEA metafrontier approach, we analyzed data for 225 Tuscan municipalities in 2016 and found that eco-efficiency is higher for publicly owned firms than mixed or privately owned firms that provide MSW services. This finding advances existing literature, which calls for further research to clarify whether or not contracting out public services, such as MSW management, is the optimal model (Petersen et al., 2018). Moreover, it lends support to existing research that finds that the public provision of urban waste services is more efficient in wealthier areas (Simões and Marques, 2012). In Italy, the debate about whether and how to privatize public service delivery is still ongoing. The empirical results strengthen the position of policy-makers who support public ownership of the provision of local services, such as waste and water management.

The increased knowledge of the factors affecting eco-efficiency in MSW services can inform the development strategies, policies, and benchmark activities of national and local regulators. Moreover, it can provide insights for defining regulatory frameworks, including incentives and penalties for municipalities, and for improving their commitment to meeting targets for increases in sorted waste and reductions in unsorted waste produced.

A limitation of this study is the relatively low number of private waste service operators evaluated compared with the number of public and mixed operators. While the conclusions apply at the Tuscan municipality level, they may not necessarily be generalizable to the national and international levels. Hence, further research is needed to extend the analysis to the national and international level by including additional waste service operators in the dataset. Moreover, future studies could include additional external variables, such as the presence of commercial and industrial activities for each municipality, and extend the dataset to include recent data, in order to allow longitudinal analysis. Finally, environmental performance indicators, such as improvement in the percentage of separate collections, greenhouse gas emissions, and noise generation due to MSW collection in each municipality, could be included in further analysis.

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.2020.02.028.

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