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Evaluating Joint Environmental and Cost Performance in Municipal Waste Management Systems through Data Envelopment Analysis: Scale Effects and Policy Implications

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Abstract

The widespread need to reduce public expenditure and meet the targets for separate collection established by current national and European legislation requires regulatory authorities to reorganize their municipal waste management systems to improve both their economic and environmental performance. This process can be helped to a great extent by the availability of empirical measures of comparative efficiency. Adding to the literature that evaluates this through data envelopment analysis (DEA) – usually focused on economic (cost) efficiency alone – this article proposes a joint evaluation of the two aspects through a modified DEA model that includes unsorted waste as an undesired output to be minimized. The article also provides an application using data for 289 municipalities located in an Italian region, Abruzzo, for the period 2011–2013. The main focus of the empirical analysis is on dimensional aspects. In particular, comparing the results obtained through DEA models based on different hypotheses concerning returns to scale, in the first place it is verified whether a particular municipal dimension emerges as an efficient benchmark, and secondly if waste collection is organized above or below its optimal scale in the municipalities taken into consideration. Tobit and probit regression models are then applied to some of the results to isolate the influence of territorial specificities on different kinds of scale inefficiencies. The information obtained allows to shed light on the usefulness of designing multi-municipal optimal territorial areas (OTAs) to improve the joint benefits of environmental and cost efficiency in waste collection, and to understand which variables the regulator should preferably take into account in the process.

Keywords: Municipal Waste Management Systems (MWMSs), Data Envelopment Analysis (DEA), Environmental and Economic Performance, Scale Inefficiencies, Undesirable Outputs, Optimal Territorial Area (OTA).

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1. Introduction

During the last two decades, almost every municipality throughout the European Union has suffered from severe budgetary constraints, with the prospect of progressive shrinkage in the resources available in the near future (Zafra-Gómez et al., 2013). It is therefore not surprising that the organization and economic performance of municipal waste management systems (MWMSs)[1], which are commonly responsible for a significant share of local governments' total expenditure, have become a crucial issue for local policymakers. Research on organizational and technical strategies aimed at improving their economic efficiency has increased exponentially (Simões and Marques, 2012), so that an extensive literature is now available.

A relevant proportion of this literature is composed of benchmarking studies, the final purpose of which is to identify and describe best practices. Data envelopment analysis (DEA) is the most widely applied method in this field (Thanassoulis, 2001). It provides a measure of the relative efficiency of a set of homogeneous decision-making units (DMUs), which use multiple inputs to produce multiple outputs when no exact knowledge about the functional form of the production or cost function is available (*non-parametric method*). Less frequently, other non-parametric methods have been used, such as the free disposal hull (FDH) approach, as well as parametric methods (requiring a preliminary specification of the functional form of the production frontier), such as stochastic frontier analysis (SFA) and deterministic frontier analysis (DFA) (see Appendix A).

Early applications of these methods in waste management go back to Bosch et al. (2000), who investigate the relation between technical efficiency and the public or private management of collection services, and to Worthington and Dollery (2001), who measure pure technical efficiency and scale efficiency in separate collections at the municipal level. The former use both parametric models (DFA and SFA) and non-parametric models: two input-oriented DEA models with variable returns to scale (VRS), the first with exogenous variables and the second without them, as well as the FDH approach. The latter implement an output-oriented DEA model with constant returns to scale (CRS) and VRS.

Given the considerable role of non-discretionary inputs or exogenous variables in the assessment of technical and scale efficiency, an intense debate has developed in the literature concerning the most appropriate econometric tools to be used in association with DEA (Liu et al., 2016). The main options under discussion are the maximum likelihood estimation of a truncated regression (Simar and Wilson, 2007), the OLS regression model (McDonald, 2009), and the fractional regression model (Ramalho et al., 2010). Banker and Natarajan (2008) show also that the tobit model and OLS are suited to this context and that their application gives quite similar results.

In the specific field of waste services, the tobit model has mainly been applied. For example, Moore et al. (2001) and Segal et al. (2002) focus on urban municipalities in the United States, while Marques and Simões (2009) focus on waste service operators. In these papers, the results of CRS and VRS input-oriented DEA are compared, and then the scores obtained by each DMU are regressed through the model on different sets of exogenous (external) factors. A similar approach is used by Boetti et al. (2012), aiming to assess whether the inefficiency of local governments in a wide range of municipal services (including environmental management) is affected by the degree of vertical fiscal imbalance. To this end, the tobit model is applied to efficiency scores computed by applying an input-oriented DEA model with VRS and SFA. A slightly modified approach can be found in the methodological contribution of Rogge and De Jaeger (2013), which proposes the use of an adjusted version of the DEA model (shared inputs DEA) for evaluating the cost efficiency of waste collection at the municipal level, together with the usual tobit model to take account of exogenous variables.

[1] For convenience, a list of the acronyms and abbreviations used in the text is provided in Appendix B.

A more recent strand of literature has addressed the same problem through multi-stage or mixed DEA approaches. García-Sánchez (2008) uses a four-stage approach by applying two models with VRS (input-oriented and output-oriented), and two with CRS to assess both technical and scale efficiency in the provision of street cleaning and waste collection, while Simões et al. (2010) apply a non-parametric double bootstrap model to estimate the effect of various explanatory factors on the efficiency scores obtained by urban waste utilities. Simões et al. (2012a) use the traditional DEA method, bootstrap DEA, and Törnqvist and Malmquist productivity indexes to determine the efficiency of waste collection services and the productivity of waste treatment services provided by urban waste utilities, and to identify critical determinants of efficiency at the municipal level. Finally, Simões et al. (2012b) evaluate the performance of 196 municipal waste collection services in Portugal by applying a DEA model, and to provide robustness to their evaluation, they make use of bootstrapping and the order-m method.

All the above studies focus solely on the economic (cost) dimension of MWMS performance. However, the rapid worsening of the conditions of sustainability of urban systems in the last few years, and the need to find satisfactory solutions to ecological waste disposal, have made it clear that the organization of MWMSs should also be functional in terms of the achievement of environmental goals, even if this implies higher costs in the organization of their services.

With a view to attaining this, extensive and articulate regulation has been adopted throughout the European Union, determining different results at the national and regional levels (Rogge and De Jaeger, 2013). European Directive 2008/98/CE has provided detailed guidelines for MWMSs, setting specific targets for the process of the preparation of waste for reuse and recycling.[2] To this European framework, national disciplinary measures are to be added (some of which are even pre-existing). In Italy, for example, Legislative Decree no. 152/2006 (the so-called *Environmental Code*), sets targets at the local level in terms of separate collection,[3] integrating the European legislation and contributing to the rigid configuration now assumed by the sector. Moreover, further regulation is often adopted at the local level to establish certain organizational and territorially sensitive aspects of the services (geographical context, private or public nature of the operator entrusted with the service, operating procedures for the collection activity, if and when the responsibility for the collection of some materials lies with the municipality, etc.).

One of the inspiring principles of this articulate framework is that achieving the target levels set for separate collection should be a prerequisite for the evaluation of efficiency. Unfortunately, the performance of MWMSs varies widely, even under this specific perspective. In Italy, for example, given the tight budgetary constraints to which most municipalities are subject, many of them have been unable to invest the resources needed to obtain improved results; when this has not been the case, different strategies (public ownership, private ownership, public–private partnership) and operational solutions (door to door or proximity collections, etc.) have been adopted according to the financial resources available at the local level and local political priorities. Thus, substantial differences can be observed both in the amount of separate collections attained by each municipality and in the total expenditure.

[2] By 2020, preparation for the reuse and recycling of waste materials of at least paper, metal, plastic, and glass from households, and possibly from other origins to the extent that these waste streams are similar to waste from households, is to be increased to a minimum of 50% overall by weight. Again, by 2020, preparation for reuse, recycling, and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste, excluding naturally occurring material defined in category 17 05 04 in the list of waste, is to be increased to a minimum of 70% by weight. Furthermore, art. 11, no. 1 of the cited Directive states that "Member States shall take measures to promote high quality recycling and, to this end, shall set up separate collections of waste where technically, environmentally and economically practicable and appropriate to meet the necessary quality standards for the relevant recycling sectors."

[3] According to Legislative Decree no. 152/2006, separate collection at the local level should have reached 65% by the end of 2012.

In such a situation, a comparison between MWMSs based on cost efficiency alone can be misleading, and to support effective decision making and correctly identify best practices, joint assessment of cost and environmental performance is desirable, if not essential. Despite the crucial relevance of such an approach, the available literature tends to confront one issue at a time, with only a few exceptions that mainly use multi-criteria analysis (Bonoli et al., 2015).

To the best of our knowledge, DEA models have never been employed for this purpose. This is the reason why in this paper a proposal is presented to integrate both economic and environmental factors within a DEA framework for the evaluation of MWMSs. In what follows, a two-step analysis is performed. In the first step, a CRS- and a VRS-modified DEA are applied, where the MWMS is considered as a production process the input of which is the annual amount of municipal expenditure for waste services, and the outputs of which are represented by both tons of separate collected waste and tons of unsorted waste. The latter represents an undesirable or "bad output" that should be reduced to improve the performance of the system (Scheel, 2001; Seiford and Zhu, 2002) as for each possible level of waste produced by a municipal system, the lower the amount of unsorted waste, the higher the amount from separate collection.[4] For this reason, in the proposed model the undesirable output can be treated as an input to be minimized. This is a methodology consolidated in the environmental field (Chen et al., 2015; Coli et al., 2011; Song et al., 2015; Yang et al., 2015; Yin et al., 2014), and also in health care (Cheng and Zervopoulos, 2014; Matranga and Sapienza, 2015), and in business applications (Wu et al., 2014), but it has never been used for evaluating the performance of municipalities in the waste management sector.

The main focus in this step of the analysis is on dimensional aspects. In particular, the DEA models are used for three purposes: the first is to detect the relative efficiency of the MWMSs under consideration; the second is to verify if a particular municipal dimension emerges as an efficient benchmark; the third is to verify if the MWMSs are operating above or below their optimal scale. The results obtained will be used to discuss the opportunity for promoting territorial aggregations with a view to improving efficiency. In the second step, tobit and probit regression models are applied to some of the results obtained in the first step to isolate the influence of territorial specificities on the economic and environmental performance of municipalities in the provision of waste services. This analysis can shed some light on the variables that should be taken into account by the regulatory authority in the design of the optimal territorial partitions in which services should be organized.

In particular, the analysis focuses on 289 Italian municipalities located in an Italian region, Abruzzo, for the period 2011–2013. The choice to apply the proposed method at the regional level depends on the fact that such a dimension is, at the moment, unique in granting a coherent and common regulatory framework. As mentioned above, many organizational decisions crucial for the performance of waste services (such as the extension of the area to be served by single operators, or the kind of separate collection to be implemented), are adopted at the regional or local level. As the performance obtained by MWMSs varies widely on a territorial basis, referring to a specific regional context makes it possible to prevent the analysis being influenced by regulatory differences not linked to organizational/managerial efficiency.

The choice of Abruzzo is based both on data availability and also its regulatory specificity. The current national legislation on waste services is inspired by the idea of unifying the organization of services in areas composed of a number of adjacent municipalities, chosen to improve technical efficiency and exploit economies of scale/scope/density. However, in Abruzzo, during the whole

[4] Furthermore, the minimization of unsorted waste also minimizes the amount of waste at risk of going to landfill and related costs. Waste from separate collections is stocked in plants (so-called platforms), where it can be purchased or taken by recyclers; unsorted waste is processed in mechanical biological treatment (MBT) plants, and the proportion of waste that cannot be used for other purposes can be disposed of in landfill sites, the owners of which are paid either by the municipality or by the firm managing the collection operations on a "per ton" basis.

period under scrutiny, the responsibility for organizing waste management systems was still fragmented at the municipal level (in Italy only Emilia Romagna, Umbria, and Basilicata were in the same situation). Thanks to such fragmentation, it is possible to study the relation between efficiency and size without the filter of regulation, and to use DEA to detect if and when the aggregation of adjacent municipalities could be useful in improving both environmental and economic efficiency. In this regard, the case study provides an example of how DEA can be used in association with econometric tools in support of the regulatory decision-making process when the optimal dimensioning of the territorial areas in which a single operator should be entrusted with the service is under scrutiny.

The remainder of the article is organized as follows. Section 2 provides a description of the methodologies adopted to evaluate the performance of the municipalities and to isolate the influence of territorial specificities. Section 3 briefly describes the legislative framework, and presents the data and variables used. Section 4 presents and discusses the results obtained, and finally, Section 5 contains some concluding remarks.

2. Methodology

2.1 The data envelopment analysis approach

DEA is a linear programing technique for measuring the relative efficiency of a set of organizational units, also called decision making units (DMUs). Charnes et al. (1978) proposed the following basic linear model, known as the Charnes–Cooper–Rhodes (CCR) model, which has an input orientation and assumes CRS of activities:[5]

$e_0 = min\theta_0$, subject to

$$\theta_0 x_{ij0} - \sum_{j=1}^{n} \lambda_j x_{ij} \geq 0,\ i = 1, \dots, m \qquad (2.1)$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rj0},\ r = 1, \dots, s, \qquad (2.2)$$

$$\lambda_j \geq 0, \forall j \qquad (2.3)$$

where y_{rj} is the amount of the r-th output to unit j, x_{ij} is the amount of the i-th input to unit j, λ_j are the weights of unit j, and θ_0 is the shrinkage factor for DMU j_0 under evaluation. This linear programing problem must be solved n times, once for each unit in the sample, to obtain a value of θ for each DMU. The efficiency score is bounded between zero and 1: a technically efficient DMU will have a score of 1.

Banker et al. (1984) modified the above model to account for situations of VRS. Their model, known as the Banker–Cooper–Charnes (BCC) model, differs from the basic CCR model only in that it incorporates a convexity constraint in the previous formulation:

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad (2.4)$$

This constraint reduces the feasible region for DMUs, which results in an increase in efficient units.

[5] If an activity (x, y) is feasible, for every positive scalar t, the activity (tx, ty) is also feasible.

The technical efficiency of the analyzed DMU j_0 can be determined either under input reduction or output expansion orientations. In an input-oriented model, the efficiency score of a DMU represents the minimum radial contraction to its input level that is feasible given its output levels; in an output-oriented model it represents the maximum radial expansion of its output that is feasible given its level (Cooper et al., 2004).

However, standard DEA models are not suitable in contexts in which at least one of the variables that have to be radially contracted or expanded is not a "good". For example, in the context of environmental performance, some production processes may also generate undesirable outputs (outputs that have a negative impact on the environment), which need to be decreased to improve the performance of a unit (Seiford and Zhu, 2005). In addition, a symmetric case of inputs that should be maximized may also occur (desired environmental effects). Hence, classic DEA models have to be modified to extend the analysis by also considering the presence of variables that exert an impact on the environment. For this purpose, a new model type of DEA is used which incorporates environmental harms as inputs and environmental benefits as outputs, while also seeking to minimize and maximize them, respectively (Coli et al., 2011).

Let us assume that n DMUs, indexed by $j=1,\ldots, n$, produce s different desirable outputs and z different undesirable outputs from m different inputs and w environmental benefits. To assess their technical input efficiency, the following two additional constraints, (2.5) and (2.6), are included in the two models considered:

$$\theta_0 h_{tj0} - \sum_{j=1}^{n} \lambda_0 h_{tj} \geq 0, \quad t = 1, \ldots, z \tag{2.5}$$

$$\sum_{j=1}^{n} \lambda_j e_{vj} \geq e_{vj0}, \qquad v = 1, \ldots, w \tag{2.6}$$

where h_{tj} is the amount of the t-th undesirable output for DMU j and e_{vj} is the amount of the v-th environmental benefit for DMU j.

It should be recalled that the CCR model yields an evaluation of overall efficiency. The BCC model, on the other hand, provides solely an estimate of managerial/organizational efficiency at the given scale of operation for each unit, thus isolating the effects of operational scale (Ramanathan, 2003). The divergence between the CCR and BCC efficiency scores captures the impact of inefficient scale size on the performance of the unit concerned. This divergence can be measured through a scale efficiency ratio (SER) as follows:

$$SER_j = Eff_j^{CCR} / Eff_j^{BCC} \tag{2.7}$$

where Eff_j^{CCR} is the efficiency score calculated with CCR model for the *j-th* DMU under evaluation and Eff_j^{BCC} is the efficiency score calculated with the BCC model for the *j-th* DMU under evaluation. Looking at the SER, it can be immediately noted how far a DMU is from its most productive scale size (MPSS hereinafter). On the basis of the SER alone, unfortunately, it is not possible to determine whether the DMU under investigation is operating above (i.e. whether it exhibits decreasing return to scale) or below (i.e. whether it exhibits increasing return to scale) the MPSS. Thus, the efficiency scores under decreasing returns to scale (DRS) must be calculated. If the DRS score is equal to the CRS score, the DRS and CCR technologies coincide and the firm is operating below optimal scale size; if the DRS score is equal to the BCC score, the dimension of the DMU is above optimal scale size (Bogetoft and Otto, 2011, p. 101).

2.2 Regression analyses

To shed some light on how exogenous (contextual) factors affect the economic and environmental performance of MWMSs, three regression analyses are performed. In particular, the aim is to determine if and in which direction certain settlement, urban, and socio-economic features of the municipalities taken into consideration influence: a) the measures of performance obtained through the application of the BCC DEA model (this model is preferred over the CCR to consider only organizational/managerial inefficiencies); b) the greater or lesser distance of a municipality from the optimal operational scale; c) the fact that a municipality operates above or below the optimal operational scale.

To measure the impact of the exogenous variables on the BCC scores, the coefficients of the following tobit model are estimated:

$$Y^* = \beta_0 + \beta_1 X_i + \varepsilon_i^* \text{ with } i = 1, \dots, n, \text{ and with the observed data } Y \text{ given by: } Y_i = \begin{cases} Y^*, & if\ 0 < Y_i^* \leq 1 \\ 0, & if\ Y_i^* \leq 0 \\ 1, & if\ Y_i^* > 1 \end{cases} \tag{2.8}$$

where Y_i is the BCC score; Y^* is a latent variable; β_0 is the intercept; β_1 is the vector of regression coefficients, estimated by applying the maximum likelihood estimation method; X_i is the vector of explanatory variables (presented in the next section); and ε_i^* are i.i.d. error terms. As the BCC scores vary between zero and 1, a tobit regression model with lower and upper limits of the outcome variable has been estimated.

With the aim of determining the influence of the exogenous variables on the optimal dimensioning of the service in each municipality, the same (2.8) model is estimated but substituting the BCC Score with the SER. As will be explained in what follows, given the peculiar constraints to which MWMSs are subject, the main strategy for gaining efficiency among neighboring municipalities operating above the optimal scale is to put two or more of them under a single waste management system and permit the re-organization/rationalization of services at such multi-municipal level. Keeping this idea in mind, a third regression is performed to evaluate if some of the variables considered are among the possible determinants of the fact that an MWMS operates above or below its optimal scale. The results obtained can enable to identify the distinctive features of the best candidate to be considered for the merging. For this purpose, the dichotomous variable Y (which is taken as 1 if the municipality operates above the optimal scale and zero otherwise) is used, and the probability of the "above optimal scale" event is estimated according to the following probit model:

$$Pr(Y = 1|X) = \phi(X^T\beta), \text{ with } Y = \begin{cases} 1, & if\ \ Y^* < 0 \\ 0, & otherwise \end{cases} \tag{2.9}$$

where ϕ is the cumulative distribution function of the standard normal distribution; X is the vector of the explanatory variables assumed to influence the status "above optimal scale size"; β is the vector of regression coefficients, estimated by applying the maximum likelihood estimation method; Y^* is an auxiliary random variable defined as:

$$Y^* = X^T\beta + \varepsilon \tag{2.10}$$

where ε is an error term.

3. The case study

The Italian government started to work on the reform of waste services in the second half of the 1990s, with the aim of optimizing their management so as to improve both economic and environmental efficiency (INVITALIA, 2013a, 2013b). The basic strategy was to overcome the geographical fragmentation of existing service provision and promote managerial integration among the different activities involved in the waste cycle. To achieve these objectives, Legislative Decree 22/97[6] (known as the "Ronchi Decree") required waste services to be provided by a single operator for each Optimal Territorial Area (OTA), a territorial partition specifically designed to exploit fully economies of scale/scope/density (Massarutto, 2010). The same decree specifies that a single authority for each OTA (on the board of which all the municipalities that make it up are represented) is responsible for the choices made to organize/coordinate the entire waste cycle (public management, private management or public–private partnership, concession to operate the services, tariffs, etc.).

The intention to gather multiple neighboring municipalities under a single organization has also been reconfirmed by recent legislative interventions, but with some changes. Article 34 of Law 221/2012 establishes that the OTA authority is not obliged to entrust the management of the collection service to a single operator; this is because past experiences led the legislator to conclude that "optimal organizational size" and "optimal managerial size" do not always coincide. It is thus possible that when the only way to organize an efficient exploitation of waste infrastructure (landfills, incinerators, etc.) is to include in the OTA the whole regional territory, an OTA itself can be divided into multiple sub-areas if specific services (collection, treatment, etc.) can achieve economic efficiency at smaller territorial scales (as in the case of Puglia, for example, where each OTA has been divided into multiple "optimal collection areas"). In this case, several operators can be entrusted with the service, one for each sub-OTA, under the supervision of the OTA authority, which guarantees the coherence of the whole system.

What emerges from this regulatory framework is that one of the most important decisions for the OTA authority is to identify the smallest dimensional levels at which efficiency can be achieved in the provision of the collection service. As mentioned in the introduction, in Abruzzo (where a single OTA has been established) collection services are still fragmented at the municipal level, which makes this region an ideal case to evaluate the utility of methods to measure and compare the performance of the municipalities. Two relevant issues arise: a) the assessment of the level of efficiency at which the services are currently provided, b) whether or not an aggregation of municipalities is desirable to improve the results obtained.

3.1 Data and variables

The data used are related to 289 Municipalities for the period 2011–2013[7]. Table 1 shows the descriptive statistics for the population of the sample and Table 2 the upper bound value of each decile of our sample (data retrieved from ISTAT, the Italian National Institute of Statistics).

[6] This has transposed EC Directives 91/156/CEE, 91/689/CEE and 94/62/CE. Since its enactment, this decree has been modified by several laws, in particular the so-called Environmental Code (Legislative Decree 152/ 2006), which has absorbed and repealed the former legislation.

[7] There are 305 Abruzzo municipalities, but those (16) for which not all required data are available were excluded from the analysis.

Table 1. Descriptive statistics for the population of the municipalities of Abruzzo, years 2011–2013

	Minimum	Mean	Maximum	Standard Deviation	Median
Population 2011	80.00	4,298.54	117,166.00	10,293.60	1,441.00
Population 2012	81.00	4,295.01	116,846.00	10,278.87	1,440.00
Population 2013	85.00	4,382.91	121,325.00	10,646.33	1,419.00

Table 2. Upper bound values of deciles for the population of the municipalities of Abruzzo, years 2011–2013

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
2011	359.6	572.9	884.2	1,099.7	1,441.0	1,897.1	2,812.0	4,419.5	8,925.4	117,166.0
2012	353.0	571.1	882.0	1,099.2	1,440.0	1,888.1	2,814.2	4,407.7	8,905.8	116,846.0
2013	359.4	569.3	874.8	1,112.4	1,419.0	1,895.6	2,834.2	4,411.4	8,959.6	121,325.0

As already said in the introduction, to evaluate the modified DEA model, three variables are taken into account: a single input (waste costs, i.e., the amount of annual expenditure for the urban sanitation service, expressed in euros) and two outputs, one desirable (waste from separate collection, expressed in tons) and one undesirable (unsorted waste, expressed in tons). Data on separated waste and unsorted waste were obtained from the Italian Institute for Environmental Protection and Research (ISPRA), while the amount of annual expenditure on the urban sanitation service for each municipality was extracted from AIDA PA, a database compiled by Bureau van Dijk, which contains financial data for Italian local public authorities. Table 3 contains the main descriptive statistics of the variables analyzed.

Table 3. Descriptive statistics for the variables used in the DEA efficiency analyses, years 2011–2013

Variables	Minimum	Mean	Maximum	Standard Deviation	Median
2011					
Waste costs (x)	4,100.00	1,025,721.68	105,602,636.00	6,433,901.02	197,558.00
Unsorted waste (z)	22.14	1,431.34	49,735.80	4,193.05	406.11
Separated waste (y)	1.08	736.65	19,721.42	2,104.25	115.79
2012					
Waste costs (x)	3,897.43	875,888.93	53,830,430.05	3,642,960.45	220,537.86
Unsorted waste (z)	22.06	1,250.14	47,429.58	3,782.10	322.13
Separated waste (y)	0.59	804.02	22,977.17	2,278.93	150.09
2013					
Waste costs (x)	3,852.41	786,707.20	23,425,145.48	2,293,511.77	221,234.62
Unsorted waste (z)	8.21	1,094.80	47,938.88	3,549.58	302.57
Separated waste (y)	1.08	866.62	19,547.38	2,217.65	177.83

The explanatory variables used in the regression analyses belong to the set of the variables normally used in the literature (see Appendix A) and have been chosen on the basis of data availability. They are: the surface area of the municipality (AREA); the elevation above sea level of the municipality (ELEV), an index of the spatial dispersion of the population (DISP), which is the ratio of the number of inhabitants living in scattered housing clusters and the population living within the administrative boundaries of a municipality; the length (kilometers) of internal roads of a municipality (STREET); an index of tourist carrying capacity or accommodation density (TOUR), which the ratio of the number of beds available in tourist accommodation located in the municipality; per capita income (INC). Table 4 shows summary statistics for these variables. The Pearson's correlation coefficient between the explanatory variables (two x two) was investigated, to ensure that there is no multicollinearity among them (see Table 5).

Table 4. Descriptive statistics for the variables used in the regression analyses

	Min	Mean	Max	Standard Deviation	Median
AREA	4.37	35.38	473.91	35.96	26.17
ELEV	2.00	556.23	1475.00	318.57	499.00
DISP	0.00	0.24	0.97	0.23	0.18
TOUR	0.00	11.82	521.46	50.73	1.56
STREET	4.00	65.89	800.00	78.60	46.00
INC	9428.13	14340.98	22359.43	2212.13	14203.51

Table 5. Pearson correlation matrix for the variables used in the regression analyses

	AREA	ELEV	DISP	STREET	TOUR	INC
AREA	1					
ELEV	0.2125	1				
DISP	-0.1368	-0.2820	1			
STREET	0.4478	-0.2558	0.0615	1		
TOUR	-0.0415	-0.2587	-0.1017	0.1234	1	
INC	0.3421	-0.1885	-0.1497	0.4008	0.1546	1

All the data on explanatory variables were obtained from ISTAT, the only exceptions being STREET and INC, obtained from the Italian Ministry of Economy and Finance (MEF), and TOUR, which was calculated on data obtained from Open Data Abruzzo (the official portal for open data of the Abruzzo region).

4. Empirical results and discussion

4.1. Best practice analysis through modified DEA models

As already mentioned, efficiency results are computed for each municipality using DEA models with an input orientation, so their objective is to minimize inputs while producing at least the given output levels. The measures of input efficiency, summarized in the following tables, have been obtained using R software (Bogetoft et al., 2015).

Building on this basis, it is possible to explore the "dimensional" problem, focusing on three crucial aspects: 1) the evaluation of the influence of scale effects on the inefficiencies of regional municipalities; 2) the emergence of "dimensional regularities" between the efficient municipalities; 3) the evaluation of the distance of each municipality from its own optimal scale, and the implication that can be drawn. The differences between points 2 and 3 must be underlined to avoid the risk of misunderstanding. The standard confrontation between CCR and BCC for a specific

DMU can tell if scale effects exist and how much they account for. Each DMU has its own optimal operational scale with which its actual scale is confronted. It is thus possible and not infrequent that small municipalities operate above their optimal scale and large ones below it (the issue addressed in point 3). This clearly has nothing to do with the presence of scale effects “across” the distribution (what economists would call “economies of scale”), the existence of which needs to be assessed with different tools (the issue addressed in point 2).

Table 6. Comparison of the descriptive statistics for the efficiency scores obtained by Charnes–Cooper–Rhodes (CCR) and Banker–Cooper–Charnes (BCC) DEA models, years 2011–2013

Year	Minimum		Mean		Maximum		Standard Deviation		Median	
	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC
2011	0.0009	0.0220	0.1808	0.3028	1.0000	1.0000	0.1996	0.2559	0.0822	0.2182
2012	0.0010	0.0226	0.2061	0.3408	1.0000	1.0000	0.1848	0.2630	0.1556	0.2672
2013	0.0014	0.0215	0.2972	0.3686	1.0000	1.0000	0.2356	0.2535	0.2835	0.3487

Even if the efficiency scores register low levels on average for both models considered, as far as point 1 above is concerned, the results obtained (Table 6) show some interesting elements. The mean and the median are slowly increasing across years, and this holds for both the CCR and BCC models. This seems to confirm that a generalized improvement in municipal performance is taking place (possibly as a consequence of the growing attention being paid to separate collection and to the rationalization in municipal expenditure promoted by the national spending review). Second, it can be noted that the BCC mean and median scores are always greater than the CCR values, and this confirms that the municipal scale at which waste management systems are organized in the period under observation has tended to hamper the improvement of efficiency levels (too much unsorted waste and too much expenditure). Finally, the growth of the mean and median scores is greater for the CCR model (0.1164 and 0.2014 respectively) than for the BCC model (0.0658 and 0.1305). The differences between the results of the two models thus tend to diminish, as do the inefficiencies due to scale effects (this could be linked, in principle, to the *de facto* processes of integration between municipal systems realized through the concession of waste services to the same operator by different municipalities; however, this hypothesis should be the object of further analysis).

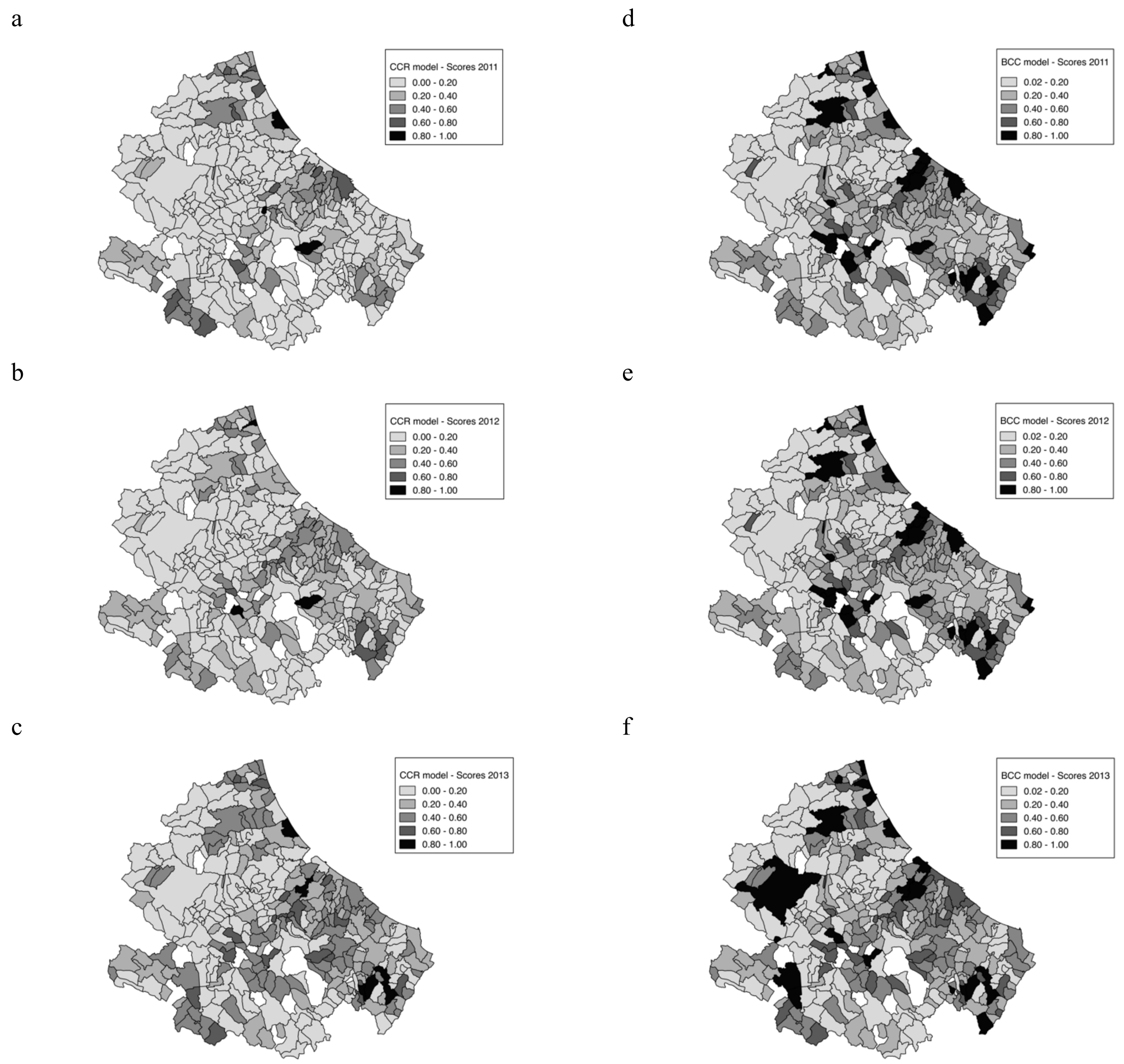
Table 7. Number of municipalities by class of efficiency score determined by Charnes–Cooper–Rhodes (CCR) and Banker–Cooper–Charnes (BCC) DEA models, years 2011–2013

Efficiency scores	2011		2012		2013	
	CCR model	**BCC model**	**CCR model**	**BCC model**	**CCR model**	**BCC model**
[0;0.2]	197	141	161	104	121	91
[0.2;0.4]	44	66	84	89	63	78
[0.4;0.6]	35	43	34	52	80	66
[0.6;0.8]	10	20	7	17	19	34
[0.8;1]	3	19	3	27	6	20
of which fully efficient	*2*	*13*	*2*	*13*	*4*	*10*
Total	**289**	**289**	**289**	**289**	**289**	**289**

“Fully efficient DMUs” are decision making units which obtained a DEA score equal to 1

These intuitions are also confirmed by the distributions of the efficiency scores of the CCR and BCC models (Table 7). In general terms, it is quite evident that in the years under scrutiny, a large majority of the municipalities obtain very low ratings for both DEA models. However, the CCR model is characterized by a greater number of inefficient municipalities and a lower number of efficient municipalities with respect to the BCC model. In other words, a relevant number of municipalities operate at a non-optimal scale, so that by sterilizing the scale effects the score distribution becomes much more balanced. As already remarked, the scale inefficiency seems to be slowly reducing during the period, and the two distributions show a tendency to become more similar (Figure 1 provides a comparison between the CCR and BCC scores obtained by the municipalities).

Figure 1. Efficiency scores of the municipalities of Abruzzo determined by Charnes–Cooper–Rhodes (CCR) DEA model for a) 2011 b) 2012 and c) 2013, and by Banker–Cooper–Charnes (BCC) DEA model for d) 2011 e) 2012 and f) 2013



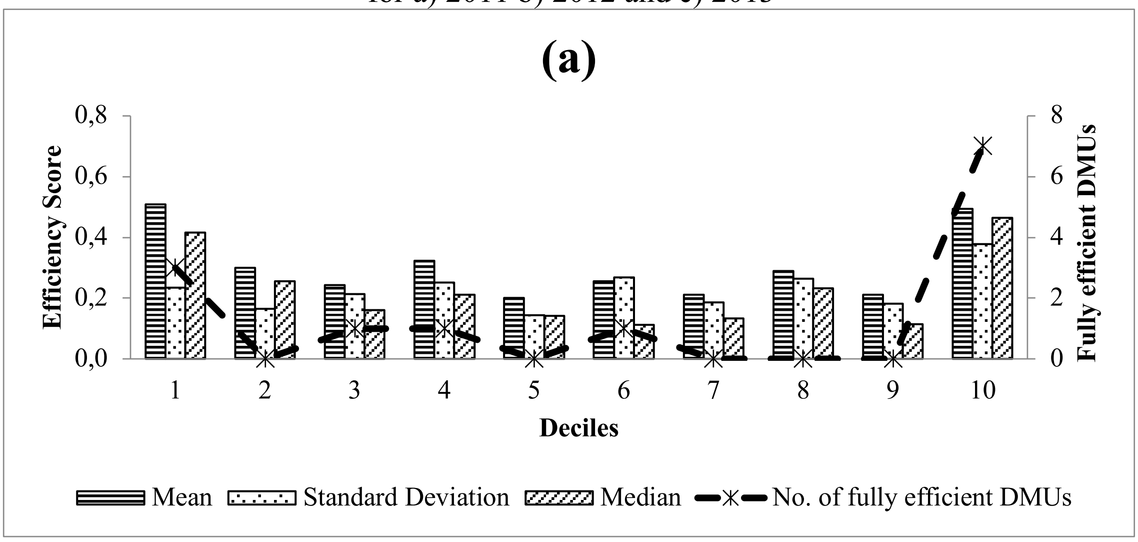
Maps created with "Quantum GIS" (QGIS_Development_Team, 2016)

The efficiency scores calculated by the BCC model (excluding scale effects) can be used to verify if there is a particular municipal dimension that tends to be more efficient than the others (point 2 above). To address this issue, it is useful to observe the distribution of the BCC efficiency score *per* decile of population (similar outcomes can also be obtained using as a dimensional variable the annual tons of waste collected). These results are shown in Figures 2(a), 2(b), and 2(c), referring to 2011, 2012, and 2013 respectively.

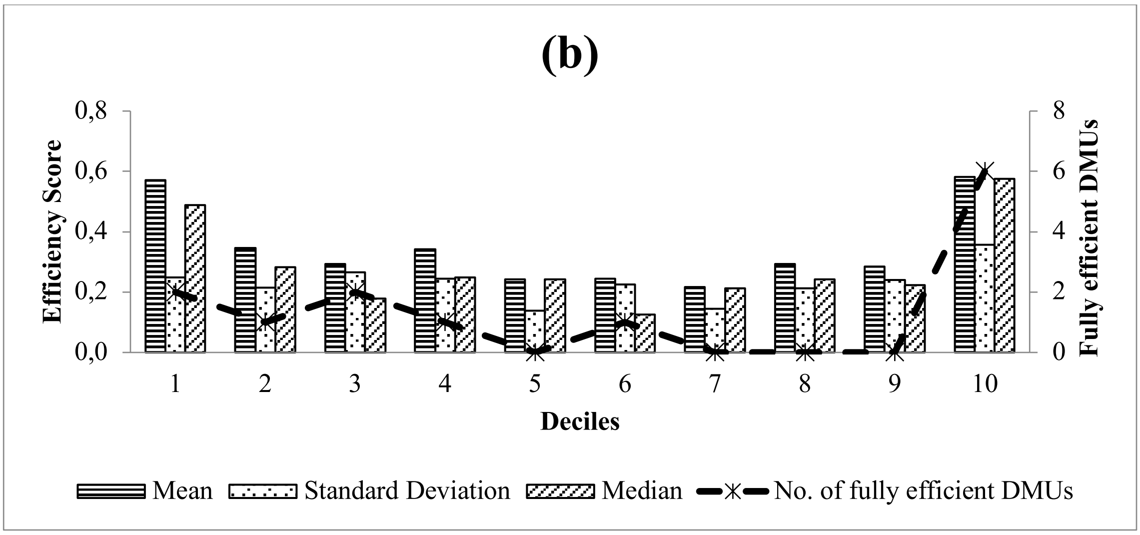
Looking at the bar charts, it can be observed that the average efficiency scores of the first and the last deciles are always the highest, so it would seem that the smallest and largest municipalities of the sample are, on average, the best performers (the upper bound value of the first decile is 354 inhabitants in 2011, 349 in 2012, and 359 in 2013; the lower bound value of the last decile is, respectively, 9367, 9343, and 9294, in 2011, 2012, and 2013). The standard deviation of the efficiency scores is very similar in all deciles analyzed, except the last in which it is higher than others. The medians of the efficiency scores in the first and the last decile are about twice those of other deciles in 2011 and 2012; in 2013, there is an increase in the medians of central deciles, but the median of the last remains the highest.

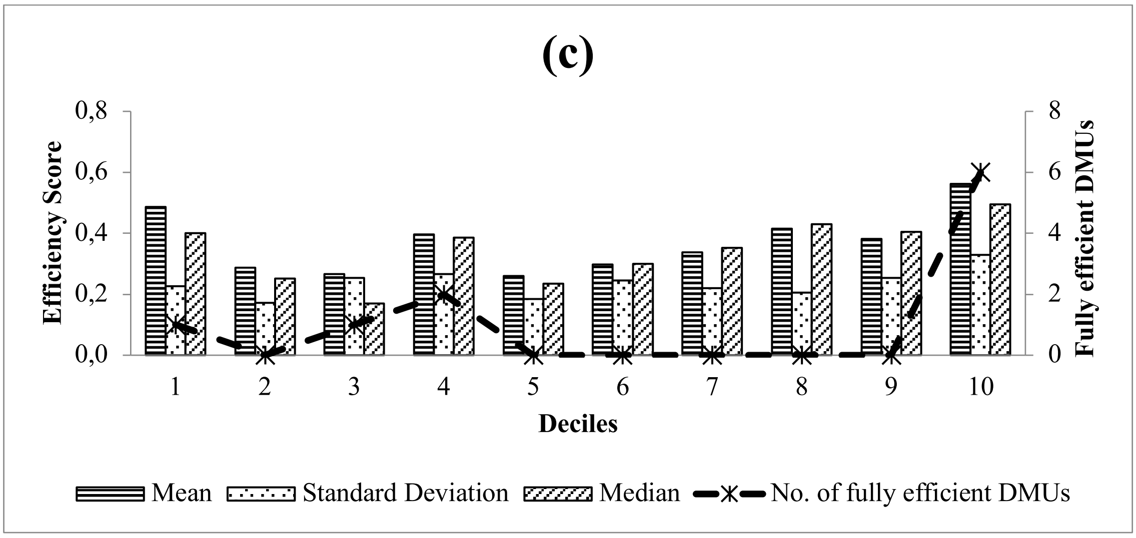
In conclusion, visual inspection of the results confirms the existence of a relevant polarization of optimal scales, with the smallest and largest municipalities (those included in the first and the last decile) tending to be more efficient than the others. The dotted line of Figure 2 shows how many municipalities in each decile obtain a score equal to 1, and must therefore be considered "fully efficient". The majority of top performers are always located in the last decile (seven in 2011, six in 2012, and 2013). Moreover, the reference set (the data relative to the number of times each efficient municipality is taken as a benchmark to determine the relative efficiency of the others)[8] seems to show that small, fully efficient municipalities are more often a reference than the large ones (except for one case in 2013). As the latter tend to perform better than the former, especially on the environmental side, it seems that the distribution of the municipalities as a whole is more oriented to separate collection than to cost reduction. Clearly, this cannot be considered a totally unexpected result, given the tight environmental targets set by legislation. From a policy perspective, the implications are quite clear: it seems to be appropriate to merge middle-sized municipalities to attain the population dimension of the largest ones as this would increase the probability of obtaining full efficiency through a reorganization of the waste collection service.

Figure 2. DEA efficiency scores showing the number of fully efficient municipalities in each decile for a) 2011 b) 2012 and c) 2013



[8] These data are not included in the text but are available on request.





"Fully efficient DMUs" are decision making units which obtained a DEA score equal to 1

4.2. Scale efficiency and the dimensioning of OTAs

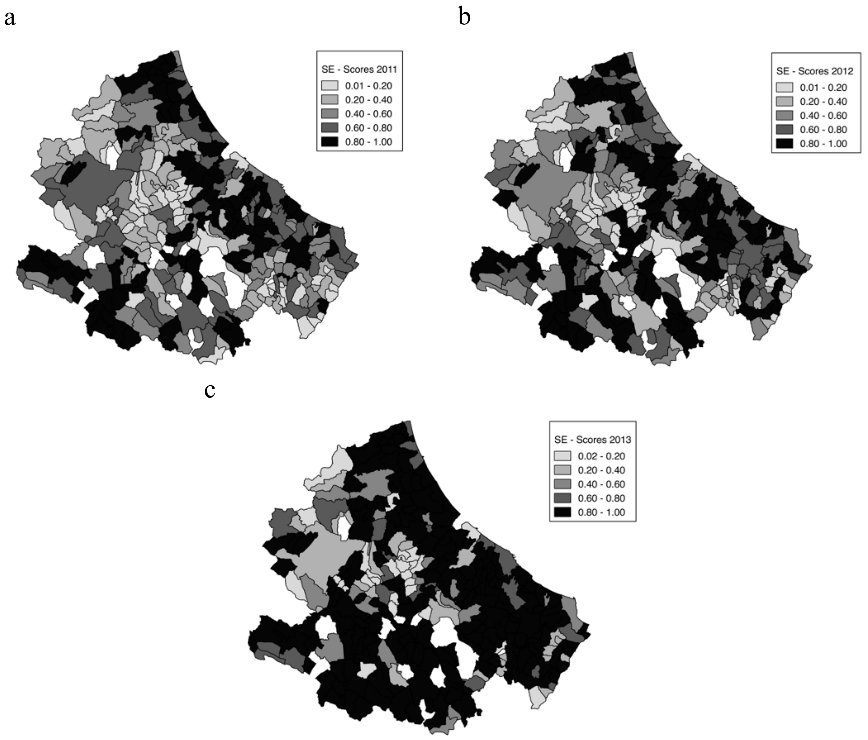
To take into account distortions due to the differences between the actual operational scale of each municipality and the optimal one, and the possible policy implications (point 3 above), the SER can be used. The SER is equal to 1 when the DMU operates at the MPSS, and the lower it is, the greater are the gains in efficiency that can be obtained by adjusting the operational scale (Bogetoft and Otto, 2011, p. 101).

Our findings show that only two municipalities register the maximum SER score in 2011 and 2012, and four in 2013. However, on average, the SER is quite high (Table 8) and it increases from 2011 to 2013. This confirms a progressive reduction of scale inefficiencies, even if it is quite evident that great improvements (about 23% on average) can still be achieved. It is also worth noting that the median becomes very high during the period, meaning that the scale inefficiencies that affect almost all the municipalities considered are particularly severe for only half of them. Figure 3 shows the evolution of the SER obtained by the municipalities.

Table 8. Descriptive statistics for scale efficiency ratio (SER), years 2011–2013

Year	Minimum	Mean	Maximum	Standard Deviation	Median
2011	0.0107	0.5667	1.0000	0.3046	0.6003
2012	0.0063	0.6230	1.0000	0.3001	0.6745
2013	0.0154	0.7692	1.0000	0.2957	0.9161

Figure 3. Scale efficiency ratio (SER) of the municipalities of Abruzzo for a) 2011 b) 2012 and c) 2013



Maps created with "Quantum GIS" (QGIS_Development_Team, 2016)

As already mentioned, calculating the efficiency scores under the assumption of DRS, and comparing the results obtained to those of the CCR and BCC models, it is possible to determine whether a municipality operates above or below its optimal scale. In this case, the data show that 25, 66, and 121 municipalities are above optimal scale size in 2011, 2012, and 2013 respectively, while all others are below optimal scale size (Figure 4). This result can be quite confusing because the trend toward the improvement of the average SER goes in parallel with an almost five-fold increase in the number of municipalities operating above their optimal scale. Moreover, a "contagion" effect seems to have been at work during the period, with the areas constituted by municipalities operating above the optimal scale progressively increasing their dimension, starting from the original sites.

Figure 4. Kind of scale inefficiency (above/below optimal scale size) of the municipalities of Abruzzo for a) 2011 b) 2012 and c) 2013

Maps created with "Quantum GIS" (QGIS_Development_Team, 2016)

How should one interpret these results from a policy perspective? The maps make it clear that scale inefficiency is a widespread and growing problem in the Abruzzo region. However, it is not easy to draw political implications given the extreme difficulty of intervention addressing the total waste produced in a municipality (which is an exogenous variable strictly related to economic, social, and cultural factors), the relation between total waste, separate collection, and unsorted waste, the fact that usually the cost of the service paid by the municipalities should only compensate (according to sometimes complex regulatory mechanisms) the costs sustained by the operators entrusted with the service, so that an excessive cost is often consequence of an inadequate organization of the last ones. Such policy implications are quite distant from what may appear at a first glance.

When an MWMS is operating above the optimal scale, both unsorted waste and the costs sustained by the municipality (which reflect those of the subject entrusted with the service) are too high to be efficient if set against the levels of separate collection obtained. In principle, when a DMU operates above the optimal scale, its operational efficiency can be improved by reducing its inputs because the consequent diminution of the output will be less than proportional. However, such an option is not viable in the case of MWMSs: A reduction in the inputs (one of which is an undesired output) to obtain a less than proportional contraction of the output would be possible only in the impractical, hypothetical case of leaving part of the total waste uncollected. In fact, at the municipal level, the amount of waste produced does not depend on the organization of the service (for this reason, an input-oriented DEA approach was adopted). Moreover, a unilateral reduction in the municipal expenditure could determine an incomplete coverage of the cost sustained by the operator entrusted with the service, against the logic of the sectorial regulation. In such a case, the only solution to hand is for the regulation authority to decide to merge two or more municipalities into a larger OTA, and to entrust only one operator (instead of the two or more pre-existing operators) with the provision of the service for the new territorial aggregation. This operator can thus (re-)arrange and (re-)organize its operational structure to the presumably greater optimal scale now required, thus improving both economic and environmental efficiency (and without incurring the strong managerial problems usually connected with downsizing).[9]

For these reasons, when municipalities steadily operate above the optimal scale, the regulatory authority has a clear sign of the usefulness of designing multi-municipal OTAs. For various reasons though, the same signal is not as clear and unambiguous when MWMSs operate below their optimal scale. In these cases, the aggregation of municipalities into wider OTAs is not the only option and sometimes it can even be of doubtful value. For example, there might be the possibility of modifying the definition of municipal waste, bringing within the scope of MWMS a portion of the waste otherwise excluded (that from commercial and industrial activities). This will produce an increment of municipal expenditure (to cover the augmented operational costs of the subject entrusted with the service), and (perhaps) unsorted waste (the inputs), but reasonably with a more than proportional increment of separate collection (the output). Also, it should be borne in mind that sometimes the situation depends essentially on the geographic, urbanistic, and demographic characteristics of the municipality. In such cases, an efficient dimensioning of the services can be impossible, for example because the population is too small and/or dispersed, the waste produced is not enough to exploit economies of scale and density, high transportation costs could be incurred to reach recycling facilities, etc. Inefficiency should then be considered unavoidable.

Along this line of reasoning, it is possible to conclude that in Abruzzo the institution of OTAs through the union of different municipalities can promote a process of improvement in both the cost and environmental efficiency of MWMSs. Moreover, the significant increase in the number of municipalities operating above the optimum scale during the period covered by the study is a clear signal of the increasing urgency of such regulatory reform. It is also reasonable that the OTAs should be designed at the provincial level, but visual inspection does not permit the conclusion that a single regional OTA would be the optimal solution, unless it may prove necessary to subsidize the services in municipalities in which they cannot be organized efficiently. To design the optimal boundaries of OTAs, further research should be performed as it is not the object of this work. It would be interesting, for example, to verify the presence of spatial autocorrelation between the municipalities once the SER and the kind of scale inefficiencies (below or above the optimal scale) are considered.

4.3 Analysis of the determinants of efficiency

The econometric analyses aimed at assessing the influence of contextual factors on the measures of performance obtained by means of the DEA models were carried out using the VGAM (Yee, 2015) and Stats (Team R Core, 2015) R packages. As the explanatory variables tend to be constant over long periods of time, they were performed on data for 2013 only (with the exception of DISP, calculated using data from the 15th Italian Population Housing Census, completed in 2011).

At this stage, the purpose of the regression was mere exploration. For this reason the discussion of the results obtained is focused only on the algebraic sign of the coefficients and not on their magnitude. Furthermore, it has to be borne in mind that a high R-squared should not be expected as DEA scores are mainly determined by the internal organization of the "productive process".

[9] Of course, from the service operators' point of view, this strategy raises the problem of how to manage the necessary dimensional growth: through mergers and rationalization, through consortia, or through simple internal growth based on competition for the market. However, addressing this last issue is not the objective of the present paper and can very well be explored in subsequent studies.

External variables, like those used in the regressions, account only for small differences attributable to environmental factors not controlled by the subject that organizes the service, in this case the municipality itself. Some of these variables (referred to as "choice variables" hereinafter) can be considered by the regulatory authority in the process of designing OTA boundaries. Knowing the influence they can have on the DMU's dimensional inefficiency can thus provide helpful information.

It is not easy to formulate expectations concerning the influence of the variables considered. A consistent line of research, accounted for in the introduction to this paper, has clarified the kinds of impact they should have on cost efficiency. To the best of our knowledge, however, none of the available studies have attempted a joint evaluation of cost and environmental efficiency, and the presence of the undesired output in the proposed DEA models could significantly modify the final outcomes.

As far as BCC efficiency scores are concerned, a negative sign for AREA, ELEV, STREET, and DISP can be expected. These variables can significantly influence the operational complexity of the service, and thence its costs. At the same time, they can make it more difficult to control the way in which and the diligence with which separate collection is performed by citizens. The influence of TOUR and INC is rather ambiguous. High tourist numbers increase the total waste produced in a municipality, and thus the costs of collection, but the incremental waste is usually generated in locations (such as hotels, restaurants, etc.) in which separate collection, if not mandatory, is performed more rigorously than in private houses, a fact that can improve the environmental side of the performance of MWMSs. Also, an higher INC can generate an increase in the total waste produced (and therefore in the collection costs), but it is sometimes associated with higher environmental awareness (Crociata et al., 2015), usually paralleled by higher levels of separate collection.

The same hypotheses cannot be repeated when it is scale efficiency that is under scrutiny. In this case it is not possible to draw from the literature on the efficiency of MWMSs a set of expectations to confront the data. Instead, the regressions can be performed to understand *a)* if any of the observed variables can be considered an external determinant of scale efficiency, and *b)* their presumed (positive or negative) influence. This line of reasoning can be useful, especially from a policy perspective, as the regressions can shed some light on which territorial factors should be taken into account in the process of defining the geographical boundaries of OTAs. From this perspective, AREA, STREET, and to a lesser extent DISP, can in principle be controlled by regulatory authorities through the choice of the municipalities to aggregate, while ELEV, TOUR, and INC can be treated as exogenous control variables. Table 9 lists the results of the regressions carried out (tobit model 1 = tobit model in which the dependent variable is the BCC score; tobit model 2 = tobit model in which the dependent variable is the SER; probit model = probit model in which the dependent variable Y is dichotomous, 1 if the municipality operates above the optimal scale, and zero otherwise).

Table 9. Results of the regression analyses

Explanatory variable	Tobit model 1[a] Coefficient (Standard Error)	Tobit model 2[b] Coefficient (Standard Error)	Probit model[c] Coefficient (Standard Error)
AREA	-0.002645***	1.552	1.275
	(0.000736)	(0.8445)	-4.212
ELEV	-0.000151**	-0.323***	-1.37***
	(0.000056)	(0.06494)	(0.3424)
DISP	-0.2299***	-137.7	-888.7*
	(0.06834)	(78.84)	(413.2)
STREET	0.000786***	-0.8704**	2.708
	(0.000236)	(0.2709)	-1.929
TOUR	0.000367	-0.5537	1.595
	(0.000294)	(0.3391)	-2.369
INC	0.000007	0.03478***	0.164***
	(0.000008)	(0.00884)	(0.04471)
Residual Standard Error	0.2314	0.2703	
Multiple R-squared	0.1768	0.1663	
Adjusted R-squared	0.1589	0.1482	

[a] Tobit model in which the dependent variable is the efficiency score determined by Banker-Cooper-Charnes DEA model for the year 2013

[b] Tobit model in which the dependent variable is the scale efficiency ratio for the year 2013

[c] Probit model in which the dependent variable takes value 1 if the municipality operates above the optimal scale, zero otherwise

The symbols ***, ** and * indicate significance levels of 0.001, 0.01, and 0.05 respectively

The first column illustrates the results of the tobit regression of the BCC efficiency scores on the exogenous factors. It can be observed that only four explanatory variables are statistically significant. Of these, AREA, ELEV, and DISP show a negative sign as expected, but – at least at this stage – it is not clear why STREET shows a positive sign, against expectation.

The second column shows the results of the same regression model but using the SER as the dependent variable. Of the control variables, only ELEV and INC show a statistically significant influence, the former with a negative coefficient and the latter with a positive coefficient. This seems to mean that a higher ELEV makes it more difficult to attain an efficient dimensioning of the service, possibly as a consequence of greater operational difficulties. The circumstance, reported in the literature, that higher personal income (through higher cultural and environmental sensibility) is usually linked to a higher level of separate collection (Crociata et al., 2015) could make efficient dimensioning easier, thus explaining the second sign.

As far as the "choice variables" for the regulatory authority are concerned, it can be observed instead that the length of internal roads (STREET) is the only statistically significant explanatory variable, with a negative sign. This result is quite interesting because in the regressions performed on *BCC Scores* the coefficient of STREET is indeed positive. Thus, it is possible to conclude that a higher street extension tends to facilitate the achievement of higher levels of managerial efficiency, but with increasing difficulties in designing the organization at the optimal scale.

The third column reports the results of the probit model explaining the probability of being "above optimal scale size". It can be seen that the only variables to be statistically significant (even if with strong differences) are those that cannot be considered choice variables from the regulatory point of view. In particular, the higher the elevation of a municipality and the dispersion of the population, the lower the probability of being above optimal scale size; in contrast, the higher per capita income, the higher the probability of being above optimal scale size. The policy implication of such results seems quite clear: The best candidates for being above optimal scale – and thus merging – are coastal municipalities with high population density and high per capita income.

5. Conclusions

Many of the regulatory decisions concerning the re-organization of MWMSs could strongly benefit from accurate empirical measures of comparative efficiency. Many tools have been proposed for this purpose in recent years, with input-oriented DEA models focused on cost minimization playing a leading role in the applied literature. However, in a context in which both rationalization of public expenditure and environmental targets have to be pursued, a sound decision-making process should be based on the joint consideration of these two aspects. Unfortunately, such an approach has hardly ever been adopted in the available literature. To overcome this limitation, the use of a modified DEA model, based on the inclusion of an undesired output to be minimized (unsorted waste) has been proposed in this article. It is also provided an application of the model to data on 289 Italian municipalities located in the Abruzzo region for the period 2011–2013.

The main focus of the analysis has been on dimensional aspects. In this regard, in particular, the efficiency scores of the municipalities under the hypotheses of constant and variable returns to scale were firstly determined. In this way, the extent and distribution of scale inefficiencies across the sample (and the comparative levels of managerial efficiency once the scores were cleaned of distortions due to scale effects) were assessed. Secondly, it was verified if a particular municipal dimension would emerge as an efficient benchmark. Thirdly, it was determined if the individual systems taken under consideration were operating above or below their optimal scale. The results obtained can briefly be summarized.

The comparison between the CCR and BCC scores shows a significant presence of scale inefficiencies across the distribution, but with a gradual reduction during the period under observation. In any case, scale inefficiencies seem to be more diffused between the lower classes of the dimensional distribution of the municipalities according to the population.

The distribution of BCC scores, which measure managerial efficiency cleaned of scale effects, shows that average scores are significantly higher for the first and last deciles of the distribution of municipalities according to population (the difference probably being that municipalities in the first decile perform better from the environmental point of view, while those in the last *decile* from the cost point of view). The same deciles (the last in particular) also hold a higher number of fully efficient DMUs. It should be taken into account, however, that those included in the first decile are micro-municipalities, whose population is composed by a very small number of families with mutual knowledge and a strong sense of community. Unlike the municipalities included in higher deciles, at this dimension, separate collection has no organizational complexity, and usually requires low specific investments. Relevant cost and environmental results, therefore, can be obtained thanks to active informal cooperation/participation and a great operational flexibility: all elements difficult to replicate at larger dimensional scales. For this reasons, as far as the organization and the efficiency in the provision of the service are concerned, the smallest municipalities represent exceptional cases, with no generalizable implications. Only the largest ones should be properly considered dimensional benchmarks for joint cost and environmental efficiency.

Finally, starting from a situation in which a broad majority of the municipalities operate below the optimal scale, an almost five-fold increase in the number of municipalities operating above their optimal scale takes place during the period.

This information has been used to shed light on a particular regulatory issue: the usefulness of designing multi-municipal OTAs to improve both the environmental and cost efficiency of MWMSs. In this respect, two main conclusions can be drawn. The first is that, in general, there seems to be a dimensional threshold that must be exceeded in order to significantly improve efficiency through a reorganization of the MWMS. At least for the Abruzzo region, it is represented by the average population size of the municipalities included in the last decile. From the regulator's perspective it is therefore appropriate to merge lower-sized municipalities to reach such a threshold. The second, and more general, pertains to how to select the best candidates for aggregation. In this respect it was argued that, given the specificities of the service, they have to be found principally between adjacent municipalities which steadily operate above the optimal scale. In such a case, the regulatory authority has a clear sign of the usefulness of designing multi-municipal OTAs as a way of promoting a dimensional and operational (re)organization of the operator entrusted with the service.

A regression analysis of the results obtained through DEA on certain variables expressing territorial specificities is then performed to give some preliminary indication of which territorial aspects and dimensional characteristics the regulatory authorities should take into account in the process of designing the boundaries of OTAs.

In conclusion, the method of performance evaluation proposed in the paper could become a good decision support tool, and enter the "evaluation toolkit" of policymakers and local government authorities at various levels. It is, in fact, a flexible tool that can be improved with the inclusion of other undesirable outputs in the analysis, i.e. the amount of waste going to landfills and/or the levels of air pollutant emissions and foul smells related to the process of waste collection. With reference to desirable outputs, instead, an interesting integration would be that of considering the energy recovered from waste-to-energy plants. In this way it should be possible to keep account of the different destinations of unsorted waste after collection. Extensions like these can become of great interest in the future if the relevant data at municipal level will be made available.

Furthermore, the method proposed can also be adapted to fit several other situations. For example, it can be used for comparing joint economic and environmental performance of water distribution systems, with water losses in the distribution process as undesirable output; of local public transport, with air pollutant emissions as undesirable outputs; or even of incineration plants, with air pollutant emissions and foul smells as undesirable outputs.

Lastly, it should be taken into account that a more environmentally friendly MWMS requires higher shares of separate collection, but at the same time must be financially sustainable by the municipal community. For this reason, the DEA scores obtained through the method here proposed could be integrated with other ecological indicators in a multi-criteria analysis to measure urban environment quality, or could become a sub-component/sub-index of a composite ecological indicator for urban environment quality assessment.

Appendix A.

Table A.1 Studies conducted using the DEA approach in the waste sector

References	Methodology	Area	DMU* (Size of sample)	Year/Period	Input	Output	Exogenous Factors – Nondiscretionary inputs
Boetti et al. (2012)	DEA, SFA	Italy	M (262)	2005	Current expenditure for environmental management	Amount of waste collected	Management (values to distinguish the different management models for refuse collection: public management, public management by a firm, public management by a cooperative firm)
Bosh et al. (2000)	DEA, DFA, SFA, FDH	Spain	M (75)	1994	Containers; trucks; workers	Amount of organic material refuse collected	Density of urban population; seasonal population
Garcia-Sanchez (2008)	DEA	Spain	M (38)	2000	Containers; trucks; workers	Amount of waste collected; collection points; collection point density; kilometers of surface area washing	Tourist index (seasonal population); mean temperature; surface area for the entire town; population density; per capita income; economic activity index; group of municipalities (dummy: 1 if municipality shares some solid waste collection services with other municipalities; 0 if municipality provides the service alone); political ideology (dummy: 1=conservative ideology, 0=left-wing ideology)
Marques and Simões (2009)	DEA	Portugal	U (29)	2005	OPEX; CAPEX	Amount of treated solid waste; amount of recycled waste	Population density; GDP per capita; distance to landfill
Moore et al. (2001)	DEA	US	M (44)	1993–1999	Current expenditure for waste service; Workers	Number of citizens served	Population change 1990–1996; average snowfall, average temperature; state and local tax revenue per capita; local government share of total statewide government employees; city manager vs. elected mayor governance structure

Rogge and De Jaeger (2013)	DEA	Belgium	M (293)	2008	Current expenditure for waste service	Amount of residual waste; amount of other municipal waste; amount of packaging waste; amount of other EPR waste; amount of green waste; amount of bulky waste	Municipality typology; green and social political party (dummy: 1 if a left wing party is part of the governing coalition, 0 if otherwise); municipality demography; median income
Segal et al. (2001)	DEA	California	M (10)	1993–1998	Current expenditure for waste service; workers	Number of citizens served	Population change 1990–1996; average snowfall, average temperature; state and local tax revenue per capita; local government share of total statewide government employees; city manager vs. elected mayor governance structure; surface area for the entire town
Simões, De Witte and Marques (2010)	DEA	Portugal	U (29)	2007	OPEX; CAPEX	Amount of treated solid waste; amount of recycled waste	GDP per capita; distance to treatment facility; population density; management (dummy: 1 if private, 0 if public); regulation (dummy: 1 if utility regulated, 0 if non-regulated; composting (dummy: 1 if the facility exists, 0 in the opposite case); incineration (dummy: 1 if the facility exists, 0 in the opposite case)
Simões, Cruz and Marques (2012)	DEA	Portugal	U (196)	2008	Trucks; workers; other OPEX	Amount of residential waste collected	

Simões, Carvalho and Marques (2012)	DEA	Portugal	M (196)	2008	Trucks; workers; other OPEX	Amount of residential waste collected	Management (values to distinguish the different management models for refuse collection); distance covered by the vehicles to assure the universality of the service; outsourcing (dummy: 1 if the service is provided by a private operator; 0 if otherwise); population; surface area for the entire town; population density; GDP (regional); purchasing power; geography 1 (dummy: 1 if the municipal is on an island, 0 if it is mainland); geography 2 (variable for distinguishing southern, central, and northern regions – which have different topography and weather conditions; kilometers per container (to evaluate the economies of density); population per container (to evaluate the economies of density); number of points to discard waste
Worthington and Dollery (2001)	DEA	New South Wales	M (103)	1993	Collection expenditure	Amount of waste collected; amount of recycled waste collected; implied recyclable rate (recyclable material as a proportion of total garbage collection)	Number of users served; occupancy rate; population density; population distribution; cost of disposal index

* M=Municipality; U=Utility

Appendix B.

Table B.1 Acronyms

Acronym	Expansion
AIDA PA	Analisi Informatizzata dei bilanci Delle Aziende della Pubblica Amministrazione locale - Financial data for local public authorities in Italy
BCC	Banker-Charnes-Cooper (DEA model)
CAPEX	Capital Expenditure
CCR	Charnes-Cooper-Rhodes (DEA model)
CRS	Constant Return to Scale
DEA	Data Envelopment Analysis
DFA	Deterministic Frontier Analysis
DMU	Decision Making Unit
DRS	Decreasing Return to Scale
EPR	Extended Producer Responsibility
FDH	Free Disposal Hull
GDP	Gross Domestic Product
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale - Italian Institute for Environmental Protection and Research
ISTAT	Istituto nazionale di Statistica - Italian national institute of statistics
MEF	Ministrero dell'Economia e delle Finanze - Italian Ministry of Economy and Finance
MPSS	Most Productive Scale Size
MWMS	Municipal Waste Management System
OLS	Ordinary Least Square
OPEX	Operating Expenditure
OTA	Optimal Territorial Area
SER	Scale Efficiency Ratio
SFA	Stochastic Frontier Analysis
VRS	Variable Return to Scale

Table B.2 Abbreviations

Abbreviation	Meaning
AREA	Surface area of the municipality
DISP	Index of the spatial dispersion of the population
ELEV	Elevation above sea level of the municipality
INC	Per-capita Income
STREET	Length of internal roads of the municipality
TOUR	Index of tourist carrying capacity or accommodation density

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