**Factors Influencing Performance in Municipal Solid Waste Management — a Case Study of Czech Municipalities**

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**Abstract**

The study presents research focused on factors influencing performance in municipal solid waste management (MSWM) at the level of individual municipalities in the Czech Republic. Czech municipalities possess a specific municipal structure that is characteristic of high fragmentation, in which municipalities spatially resemble conglomerates. In spite of their typically small size, they cling to their own independence and are thus willing to assume full responsibilities in MSWM. In recognition that expenditure on MSWM is the primary concern to municipalities and that there are secondary environmental interests in waste separation, four alternative models of waste management service production are considered for a sample of 470 Czech municipalities that capture performance from different standpoints. Performance in MSWM is assessed by dint of data envelopment analysis (DEA). Full frontiers are employed simultaneously with order-*m* partial frontiers and resulting unconditional-to-conditional scores are investigated for the influence of twelve contextual factors describing operating conditions of MSWM. The analysis accounts for the fact that in this case the twelve contextual factors are found non-separable from the process underpinning the provision of MSWM. It is revealed that performance in MSWM improves with the availability of recycling consolidation facilities, but programs inciting waste separation or green waste collection do not bring about the anticipated effect. The findings are instrumental in planning of MSWM and equip municipalities with policy advice that is useful in improving performance in MSWM and subsequently in reaching ever stricter environmental targets requested over time at both national and international levels translated to a municipal level.

**Keywords:** municipal waste; separation; municipal expenditure; performance; efficiency analysis; data envelopment analysis

**1. Introduction**

Municipal solid waste management (MSWM) represents a common service provided by the public sector in developed countries worldwide. Gradually, as people became more environmentally conscious, more and more demands have been raised on the public sector in order to secure an appropriate level of service in this sphere. In the case of the European Union (EU) and more generally Europe, larger attention to the issue of waste management (WM) can be traced back to the second half of the 20th century, especially with the introduction of EU regulations in the late 1990s. Since then the global trend for waste treatment has shifted towards incineration and recycling instead of landfilling (Mazzanti and Zoboli, 2008).

In the Czech Republic, MSWM began to ignite interest in the 1990s along with the transition towards the market economy after 40 years of the Socialist regime. During the Socialist era, MSWM was generally not perceived as something of much importance, and the dominant way of dealing with any kind of municipal waste was landfilling. However, since the late 1990s and especially with the Czech Republic becoming a member of the EU in 2004, the situation regarding MSWM has improved notably, and issues of availability of infrastructure and technical aspects of waste treatment have come to the forefront. As a result, municipal waste treatment represented by a combination of landfilling, incineration, recycling and composting has improved gradually, albeit the Czech Republic has remained in overall waste treatment even more than a decade after entering the EU still amongst the bottom half of performers in the EU-27 (Castillo-Giménez et al., 2019a). Nevertheless, the observed trend is positive, and the performance of the Czech Republic in this area has been continuously crawling up the ranks.

The positive trend in waste treatment is defied by the trend in costs associated with MSWM, or municipal solid waste expenditure (MSWE). Spending on MSWM in Czech municipalities has been increasing remarkably since the advent of modern improvements in waste treatment. A poignant question here is, as with any other kind of public service, whether this expenditure is used efficiently (Førsund, 2013). By the reckoning of the authors, MSWE in the Czech Republic make up on average 2% of the annual municipal budget. Considering the variety of public services secured by a municipality together with municipal running costs, this number is much more significant than it might seem at first glance. In small Czech municipalities MSWE can amount to 10% of the annual budget, which makes the topic of performance in MSWM more pressing. In such cases, if the quantitative information about costs and produced services is available, examination of MSWM performance and its determining factors can lead to significant improvements in the overall level of public service delivery.

This paper presents a case study of Czech municipalities and is concerned with assessing their performance in MSWM and factors that drive this performance. The sample of 470 municipalities in the South Moravian Region contains unique data for 2012 that were compiled partly from official statistics, but a substantial part comes from personal engagement in their collection. Performance in MSWM is approached from the perspective of efficiency, which is a term intensively employed in studies of this sort. A municipality is viewed as a unit that runs a process in which inputs are utilized in production of WM service. This requires a postulation of the production process with a statement of inputs and outputs as well as an identification of linkages. Technically speaking, efficiency is then the ability to generate a maximum of outputs at a minimal consumption of inputs. In an attempt to avoid discussions about a selection of inputs and outputs and to assure robustness, this paper builds on four alternative production models of WM service by Czech municipalities that are applied with data envelopment analysis (DEA). The models answer to different conflicting goals that Czech municipalities must pursue in MSWM, and differ thus in their philosophy, input-output specification and orientation. Yet, they balance two additional insights: (a) the minimization of MSWE that is the pivotal interest to municipal officials once the WM service is provided or secured (Models I, II, III) and (b) the minimization of residual waste that has its benefits in the form of various savings, but still is of a lateral interest to municipal officials (Models II, III, IV). Since no universal model is posited, it is not adequate to speak of efficiency. A looser and more generic term, performance, is used instead. Models I – IV are further augmented by twelve possible drivers of performance relevant to Czech municipalities, out of which nine are operational and three are urban factors. The list of candidate factors is based on a thorough literature review and interviews with municipal officials. A good knowledge of these factors and their effect upon performance in MSWM is indispensable for policy planning and evaluation at a municipal level. The first group of factors with a discretionary nature is related to the organization of waste collection, separation or disposal in individual municipalities, whereas the second group of factors outside the control of municipalities is related to residential land use. These factors are addressed here as contextual factors instead of a much commoner term, environmental factors, so as to rule out confusion with references to ecological aspects of the environment.

A classic approach to this kind of research is two-stage DEA popular with studies of municipal performance in WM (e. g., Simões et al., 2010; Benito-López et al., 2011; Salazar-Adams, 2021), be that the double bootstrap procedure of Simar and Wilson (2007) or traditional ordinary least squares regression of Banker and Natarajan (2008). This approach necessitates that a separability condition holds, which is refuted for each model by using the testing procedure of Daraio et al. (2018). Hence, the paper applies a newer approach of Daraio and Simar (2005, 2007) to identify and judge the effect of contextual variables upon performance in MSWM. This approach may be designated as unconditional-to-conditional (UTC) analysis since performance in MSWM is measured both unconditionally and conditionally upon contextual factors. In turn, ratios of conditional to unconditional scores are regressed non-parametrically upon contextual factors. Radial DEA estimators under the convexity constraint in the style of Banker et al. (1984) are used to obtain both conditional and unconditional scores under full frontiers as well order-*m* partial frontiers. The latter has an advantage that it endorses the notion of robustness. A generalized additive model of Hastie and Tibshirani (1990) is employed in the second stage of UTC analysis. Example studies upon performance in MSWM that adopted UTC analysis are scanter and include just Ferreira et al. (2020). These studies and other studies situated in a similar arena of research (e.g., De Witte and Kortelainen, 2013; Cordero, 2015, 2017) actually use the FDH estimator of Deprins et al. (1984), and not the familiar DEA estimator.

Inspired by past efforts to measure performance in MSWM surveyed next in Section 2 and by a continuous need to improve MSWM, the goal of the paper is to examine performance in MSWM and to identify its drivers by using municipal data from the Czech Republic. Aside from gaining insights in terms of policy analysis and planning, the results add to the mosaic of performance factors in MSWM that varies across different territories with diverse economic, legislative, demographic or cultural set-ups. The novelties of the paper are several. First, this study is one of the very few studies concerned with performance in MSWM conducted for the Central and Eastern European region so far, representing a somewhat different environment compared to western countries. Second, the paper is centered upon Czech municipalities that are symptomatic of a highly fragmented municipal structure with a preponderance of very small municipalities, which in uncommon for western countries. Results of typical studies performed for western countries are not apt for smaller municipalities, whilst these results could bridge this gap. Third, the analysis considers for potential performance drivers original contextual variables, which have not been explored to date and are identified on the basis of subjective experience and judgment of municipal officials expressed during interviews or in electronic communication. Fourth, the effect of contextual variables is explored through UTC analysis with unconditional and conditional scores estimated by a radial DEA estimator in a convex technology, which contrasts with the practice of previous studies that employ the FDH estimator for simplification.

The remainder of the paper is organized as follows. Section 2 provides a concise survey of relevant literature, and provides a brief overview of the MSWM framework in the Czech Republic. Section 3 explains the methodology, clarifies the methodological choices and describes the data set on Czech municipalities. Section 4 presents the results and discusses them. Finally, Section 5 provides concluding remarks, offers some policy implications and suggests direction of future research.

**2. Literature review on MSWM and Czech conditions**

This section consists of two subsections that explain the backdrop from which the paper draws. After a concise review of empirical research focusing upon MSWM (Subsection 2.1), the framework of MSWM in the Czech Republic is exposited.

2.1 Empirical research on MSWM

Economic performance in the waste sector has been studied on numerous occasions, although dominantly for western countries. A review by Simões and Marques (2012) proves this point by summarizing and going through 107 relevant studies (78 being journal articles) published between 1965 and January 2011, with a majority of them emerging after 2000. These papers include simple costs analyses as well as both parametric and non-parametric efficiency-based approaches to performance evaluation that have become dominant in recent years. Besides categorization by the methods used and main issues addressed, chronological development is discussed as well. It should be highlighted that none of the papers reviewed by Simões and Marques (2012) focused upon a Central and Eastern European country, the Czech Republic not excluding. Since then, there has been a surge of interest in issues of MSWM in the Czech Republic (e.g., Šauer et al., 2008; Slavík and Pavel, 2013; Struk, 2017, 2018), although more recently in a comparative cross-country context (e.g., Castillo-Giménez et al., 2019a, 2019b; Martin and Puertas, 2021; Riós and Picazo-Tadeo, 2021).

Certainly, data envelopment analysis (DEA) in its variations is the most common method for performance assessment in MSWM as follows from the survey by Simões and Marques (2012) and applied work since then. Performance assessment of WM systems based on DEA has proceeded on two scales: national and municipal. In the group of cross-national studies, Halkos and Petrou (2019) compared the MSWM-related environmental efficiency of EU-28 countries using parameters like municipal solid waste generation, gross domestic product, population density and several types of emissions from waste. The results show (unsurprisingly) that countries with high recycling rates and low landfilling rates were rated as the most efficient. Castillo-Giménez et al. (2019a) created a composite indicator of performance in waste treatment for EU-27 countries during the period 1995–2016 with the conclusion that Central and Northern European countries have remain the best performers in spite of gradual convergence amongst all EU-27 countries. In another study Castillo-Giménez et al. (2019b) utilized data for the period 2015–2017 for EU-28 countries, and highlighted that one of the reasons for the outperformance of Northern and Central European countries over Eastern European ones lies in their ability to recycle and compost larger portions of waste. Giannakitsidou et al. (2020) then extended environmental performance comparisons at a national level by including circular economy criteria, taking into account not merely the waste recycling rate, but also the overall level of municipal waste generation. By doing so, several Western and Northern European countries with intensive recycling, but also extensive waste generation worsened their positions relative to countries with significantly lower levels of overall municipal waste generation.

However, studying waste management performance at a municipal level is in all likelihood more useful in revealing closer links between performance and related factors. In the group of municipal studies more emphasis is put on identification of factors that drive performance in MSWM. For instance, Kinnaman and Fullerton (1999) offered a broad overview of the trends in MSWM and its economy together with various factors that contribute to municipal waste generation, recycling and overall MSWM performance. Beigl et al. (2008) gave a systematic review of 45 modeling approaches to municipal solid waste generation and summarized effects of various municipal characteristics on MSWM performance. A different survey is by Pires et al. (2011) who conducted review of MSWM systems adopted in European countries. In order to explain heterogeneity amongst potential municipal driving factors, Lebersorger and Beigl (2011) employed regression analysis in examining the impact of more than 100 municipal indicators on municipal solid waste generation. More recent overviews of various performance drivers in waste collection services have been conducted by Guerrini et al. (2017), or Di Foggia and Beccarello (2020). In addition, a recent study by Rosecký et al. (2021) creates multiple models for waste generation at different territorial levels and identifies important influencing factors.

When considering specifically research related to performance in MSWM at a municipal level, multiple studies are available namely from Italy (Guerrini et al., 2017; Sarra et al., 2017; Sarra et al., 2019; Romano et al., 2020; Romano and Molinos-Senante, 2020; Gastaldi et al., 2020), Spain (García-Sánchez, 2008; Benito-López et al., 2011; Pérez-López et al., 2016; Díaz-Villavicencio et al., 2017; Pérez-López et al., 2018; Benito et al., 2021) and the Netherlands (De Jaeger et al., 2011; Rogge and De Jaeger, 2012, 2013). Some recent studies on MSWM performance outside Europe include Chile (Llanquileo-Melgarejo et al., 2021; Llanquileo-Melgarejo and Molinos-Senante, 2021), China (Fan et al., 2020) or Mexico (Salazar-Adams, 2021). While some of these studies did not go beyond calculating overall DEA-based performance scores for examined municipalities, others also analyzed the influence of contextual variables such as population size and density, per capita income, education level, model of MSWM provider ownership or tourism level.

Finally, two-stage DEA is a conventional method to ascertain and support the effect of possible drivers upon performance in MSWM. García-Sánchez (2008) explored MSWM efficiency of Spanish municipalities with a population over 50,000 inhabitants, and analyzed the effect of social indicators such as population size and density, mean temperature, per capita income or type of WM company ownership. Marques and Simões (2009) conducted a comparable analysis of Portuguese municipalities and confirmed significance of per capita income together with the operational environment. De Jaeger et al. (2011) conducted an MSWM efficiency analysis of Flemish municipalities with respect to waste reducing policy, and established that participation in voluntary agreements to reduce municipal waste levels was conducive to efficiency. All these three studies deployed tobit regression in the second stage, later criticized and discarded by Simar and Wilson (2007, 2011). This criticism gave rise to the dominance of the double bootstrap procedure. For instance, Benito-López et al. (2011) explored again determinants of MSWM efficiency of Spanish municipalities and identified positive effects of per capita income, tourism, or the political orientation espoused by municipal representatives. Simões et al. (2010) assessed the influence of the operational environment at a company level for efficiency of Portugal solid waste utilities, and proved that the environmental context does matter. Likewise, Simões et al. (2012a) investigated determinants of refuse collection services at a municipal level in Portugal and their results attested the importance of operating conditions. Recently, Salazar-Adams (2021) investigated efficiency of municipal waste collection of Mexican municipalities to find out that outsourced waste collection and curbside collection were factors associated with higher efficiency as opposed to separate waste collection. Finally, UTC analysis in assessments of MSWM performance is rare at best, and to the best knowledge, the only available application to date is Ferreira et al. (2020) who studied factors of inefficiency levels of urban solid WM service in Portugal in an attempt to relate key performance indicators of provision of WM service to efficiency.

This paper bridges the methodological and applicational gap. In the former respect, it applies two-stage DEA footed upon UTC analysis, whilst in the latter respect it focuses upon Czech conditions in MSWM that have been unexplored so far, and are unique.

2.2 Framework of MSWM in the Czech Republic

In the Czech Republic, according to the law, MSWM is a responsibility of municipalities themselves. Individual municipalities thus secure provision of WM service either on their own behalf, or, more typically, by contracting an external WM company. Terms of WM in a municipality are then set by the mandatory municipal decree that has to meet basic legislative requirements, but can be to a certain degree adapted to the specifics of the municipality. This decree articulates details of waste collection, collection frequency, options for separate collection of recyclables including the location of drop-off sites for recyclable waste, bans on illegal dumping or waste burning, and most notably the municipal waste collection fee. Citizens are then expected to abide by the regulations set in the decree. As Czech municipalities commonly range from several hundreds to dozens of thousands of people, individual municipal decrees (and subsequently the actual organization of municipal WM) can differ markedly, regardless of the comparable minimum requirements for residual and selected recyclables waste collection.

Waste collection methods differ for residual and recyclable waste. Residual waste is typically collected from bins belonging to individual single-family houses and from shared large bins belonging to multi-family houses or condominiums. Other methods like collection from plastic sacks or large volume containers are very rare, but these options are available to municipalities. For recyclable waste, collection methods are wider and include collection from bins or sacks from individual single-family houses (curbside collection), collection through drop-off sites scattered within the municipality (the most common method) or bring-in system with waste recycling centers.

In terms of collected recyclables, the current Czech legislation requires of the municipality to provide options for separate collection of paper, plastics, glass, green waste (since 2014) as well as cooking oils and fats (since 2020). This means that the municipality should secure at least one such site for collection of specified recyclables. Naturally, municipalities adjust the available capacity and number of sites for waste separation, taking into account the size of the municipality, requests from a large enough group of citizens, and the available municipal budget. Paper, plastics and glass are usually collected at a single spot as these have by far the longest tradition of separate collection. Containers for individual waste fractions vary in numbers as well, depending on the available space and capacity requirements. An alternative is curbside collection from individual houses used in some municipalities. In such cases designated sites for bring-in collection of given recyclables are very scarce or even absent, as practically they are not needed anymore, as long as everyone collects and stores recyclables until the next collection at home.

Collection frequency of residual waste varies with habits at individual municipalities and available capacities. In densely populated areas with shared waste bins residual waste may be collected several times per week, whilst in more rural areas with bins of a larger size collection may take place once every few weeks. Collection of recyclables is usually even less frequent, as the capacity available for recyclables typically lasts longer, especially with curbside collection. Of course, collection frequency can differ with recyclables of a different kind. Green waste is also subject to seasonal variation with collection occurring frequently between spring and autumn, and sporadically during the rest of the year. That said, with such size heterogeneity of municipalities, there is unsurprisingly no one-size-fits-all solution, and individual municipalities adjust their WM systems according to their needs. Common “low” frequencies are in sharp contrast with common practices in Western Europe. For instance, Simões et al. (2012a) note that less than 5% of municipalities in Portugal do not collect waste six times per week, whereas in the Czech Republic once per week is a relatively common frequency. Yet, this is a natural outcome of a likely much lower waste storage capacity per person in Portugal, as in the Czech Republic a family house is commonly equipped with at least one 240-liter bin, whilst in other countries shared bins for multiple households are often standard, and these logically fill sooner

The destination of collected waste is largely at the discretion of the WM company that contracts landfills, waste-to-energy plants for residual waste, and recycling facilities for selected recyclables, or that secures their recycling in other legal and economic ways. The municipality itself has usually a little say here since once the WM company has collected waste, it is no longer the municipality’s responsibility.

MSWM is financed by the municipality by using its own resources with means collected from citizens on the annual WM fee. The WM fee represents a locally collected tax that has currently a legal annual limit of CZK 1,000 with municipalities charging usually around CZK 600 per citizen, what amounts approximately to € 25. This fee is by Western European standards low. Fees based on collection volumes or frequencies are technically feasible, but they are rarely applied. Collected fees are on average able to cover between one half and two thirds of the total MWSE, and the municipality finances the rest of the costs from other available sources within its budget.

Besides the natural tendency of municipal officials to improve performance, an objective pressure for improvement are the EU recycling targets that are currently set to be 55% in 2025 and grow up to 65% of total municipal waste in 2035. A somewhat hidden issue here is that recycling does not equal separation, even though many authors interchange these terms as synonyms. Whilst the usual “producers” of recyclables are municipalities, it is important to note that municipalities themselves do not recycle waste — their role in this process is to “divert” recyclables from total municipal waste to recycling companies that do the actual recycling. Unsurprisingly, there exists a gap between the volumes of separated and recycled waste, and in order to achieve the EU recycling targets, waste separation levels should be naturally higher.

In the Czech Republic, this gap is reflected in national targets for municipal waste separation, according to which every Czech municipality is required to reach waste separation levels of 60% by 2025 and 70 % of total municipal waste in 2035. However, municipal data from recent years reveal that many of them struggle to reach 40% separation levels. In the light of the deadline for the EU targets, this represents a noteworthy issue. In awareness of this situation, the Czech government has recently launched new measures in order to speed up the pace at which waste separation rises. Progressive waste disposal feels for residual waste have been introduced for the upcoming years alongside a possibility of exemption from fees as long as the municipality meets the gradually increasing waste separation targets. As these higher fees directly translate into increased municipal costs, it is in the very interest of the municipality to improve its waste separation performance. Otherwise, its performance in MSWM will eventually decrease due to the higher fees paid for residual waste disposal.

**3. Methodology and data**

The paper relies upon data envelopment analysis (DEA) as a universal nonparametric technique of performance assessment (Bogetoft and Otto, 2008) that is also popular in assessing performance of WM systems, becoming to some degree an established standard in this field (e.g., Rogge and De Jaeger, 2012; Marques et al., 2012; Simões et al., 2012a, 2012b; Salazar-Adams, 2021). Although the foundations of DEA stem out of the ambitions to measure efficiency of production systems, owing to its versatility and flexibility, DEA is employed wherever the concept of inputs being converted into outputs is tenable, which is also the case of MSWM. This section summarizes and explains all crucial methodological and analytical steps that necessitated the analysis, giving in the following four subsections details on the choice of variables for performance management (Subsection 3.1), the availability of potential contextual factors of MSWM performance (Subsection 3.2) and the methodology of performance measurement recognizing the role of contextual factors (Subsection 3.3), and the data set employed in the analysis (Subsection 3.4).

3.1 Specification of inputs and outputs for WM performance

In this paper, MSWM is visualized as a process in which the ultimate service of waste collection and handling is realized with the use of numerous inputs at the disposal of a municipality. Surely, from the perspective of the Czech legislation, a municipality is primarily tasked with provision of WM service, whilst some other criteria such as economy, efficiency, effectiveness (i.e. 3 E’s of public finance) are emphasized in a general legislation. This accumulation of requirements makes of MSWM a multi-faceted and perhaps multilayered process, in which a municipality must resolve several conflicting criteria at once. These include traditional budget constraints such as cost minimization, technical goals such as high coverage of households, or sustainability aspects such as promotion of increased awareness of waste separation and recycling. These criteria complicate representation of MSWM as a simple production process with straightforward inputs and outputs, with the result being that any selection of inputs and outputs is in this case to an extent always a somewhat controversial task since it depends on the specific municipal service considered (da Cruz and Marques, 2014). Another complication is that the role of inputs and outputs may be debatable. For instance, technical variables like households serviced, area covered or total amount of waste collected may play an input role as well as an output role. If a municipality acts like a standard private entity with the goal of making its WM service accessible to as many customers as possible, certainly household numbers and area coverage are outcomes to be maximized, i.e. outputs. In contrast, if a municipality is additionally tasked to provide services in a sustainable manner, household numbers, area coverage and total waste collected are rightly positioned as non-controllable inputs that maximize waste separation, waste recycling or re-use represented with appropriate metrics positioned as outputs. A solution might be to model the WM process as a several-stage structure, or to adopt several different input-output specifications that admit a multiplicity of goals that a municipality faces. The latter approach is embraced here, and special attention is given to the fact that for a Czech municipality cost minimization represented by expenditure on MSWM (MSWE) is, to all intents and purposes, the chief concern given the tightness of a typical municipal budget. For this reason, to a municipality, preservation of good financial condition is imperative and only afterwards do other objectives of MSWM come.

Four complementary, yet barely fully exhaustive, production models of WM service are considered here in the paper in order to describe MSWM performance from different angles. These are summarized in Table 1. In addition to the economic interpretation of a model, the selection of inputs and outputs was governed by the need to stay true to volume measures and to avoid indices or percentages (see, e.g., pitfalls 4.1 and 5.1 of Dyson et al., 2001). As already pointed out, the variable pivotal to the assessment of municipal performance in MSWM is MSWE, which acts as a sole input in Models I – III. Model IV is deemed as auxiliary. Models I – III work on the assumption that MSWE represents the most important factor to municipalities in securing MSWM provision as long as minimal acceptable standards are met. Using financial resources for production is a common practice when specifying a performance assessment model based on efficiency measurement (e.g., Pérez-López et al., 2015; Cordero et al., 2015; 2017).

Models I and II are input-oriented and confront available financial resources with a goal to provide a maximum provision of waste management service. Performance in Models I and II is viewed as an ability to economize on MSWE. The difference is that whereas Model I takes into account population, built-up area and housing units as metrics of potential demand on the output side, Model II extends them by total waste and separated waste generation as metrics of actual demand. Specifying both latter metrics as outputs whose high levels are desirable implies that non-separated waste (namely, total waste less separated waste) is simultaneously minimized.

Table 1: Four different input-output configurations

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| --- | --- |
| **Model and interpretation** | **Input-output specification and orientation** |
| **Model I**  The model relates to the ability to satisfy the potential demand for services (given by different measures of population size) with a minimum of expenditure. | **Inputs:**  MSWE (CZK)  **Outputs:** Population (# of inhabitants)  Built-up area (ha)  Housing units (# of inhabited units)  **Orientation:** Input |
| **Model II**  The model relates to the ability to satisfy the potential demand (given by different measures of population size) and actual demand for services (true waste produc­tion) with a minimum of expenditure and non-separated waste production. | **Inputs:**  MSWE (CZK)  **Outputs:** Population (# of inhabitants)  Built-up area (ha)  Housing units (# of inhabited units)  Generation of total waste (t)  Generation of separated waste (t)  **Orientation:** Input |
| **Model III**  The model relates to the ability to maximize waste separation subject to the financial constraints (given by waste expenditure) and actual demand for services (true waste production) that a municipality faces. | **Inputs:**  MSWE (CZK)  Generation of total waste (t)  **Outputs:** Generation of separated waste (t)  **Orientation:** Output |
| **Model IV**  The model relates to the ability to maximize waste separation subject to the potential demand for services (given by different measures of population size) and actual demand (true waste produc­tion) that a municipality faces. | **Inputs:**  Population (# of inhabitants)  Built-up area (ha)  Housing units (# of inhabited units)  Generation of total waste (t)  **Outputs:** Generation of separated waste (t)  **Orientation:** Output |

Model I focuses on meeting the core requirement put on MSWM, which is simply the provision of waste disposal services to the citizens of the municipality. However, based on experience and discussion with municipal representatives, this might not always precisely represent the scope of required service. The scope of WM service is in Model I measured by the number of citizens with residence registered in the municipality, the built-up (urban) area, and the number of housing units in the municipality[[1]](#footnote-1). Whilst according to the Czech legislation WM service must be provided to all people living in the municipality, the other two measures give in many cases a better assessment of how many customers a municipality must service and reach (not only individuals, but also sometimes organizations that subscribe contractually with the municipality to the provision of WM service). Nonetheless, in practice none of these indicators are ideal in gauging waste collection and handling since many people living in a municipality are not registered as its citizens, many housing units are in fact uninhabited, and major parts of the built-up area do not generate waste (or littering outside the built-up area may not be a marginal issue). Hence, a combination of these indicators should allow a more complex view on the scope of WM service that must be potentially secured by a municipality, and should also offset potential distortions in the results if some municipality displays notable discrepancies in these indicators in comparison with values of other municipalities. Model I conforms to the primary goal of MSWM to secure WM service so that all inhabitants, every housing unit and the whole municipal built-up area are covered.

Model II extends Model I by adding two indicators that capture the scope of the actually provided service of the municipality to its citizens, the volumes of total waste and separately collected waste. Insomuch as both these metrics are to be maximized, non-separated waste that comes out as the residue and cannot serve recycling or re-use purposes is to be minimized. In effect, Model II in this manner injects an environmental aspect into the entire process of performance measurement and puts some emphasis upon maximizing waste separation and minimizing non-separation. For Czech conditions, these metrics have another bearing for assessment of MSWM performance. In the Czech Republic, municipalities are rewarded by the officially authorized waste package authority EKO-KOM (https://www.ekokom.cz), and the financial reward depends on the amount of separately collected recyclables, namely paper, plastics and glass. More collected recyclables translate into higher rewards entailing an additional stream of revenue. This revenue in many cases fully covers expenditure for separate waste collection, and sometimes even earns a small premium for the municipality. Maximization of waste separation is also in conformity with waste separation targets required of municipalities, under which municipalities must separate some proportion of total collected municipal waste, or they may face fines that add to MSWE. Finally, with a higher level of waste separation, municipalities receive discounts on gradually increasing landfill rates, with landfilling still representing a dominant way of final municipal waste treatment. In consequence, Model II is intended to describe municipal performance not only in provision of WM service, but also in attaining a structure of waste collection that it provides financial benefits, to say nothing of the environmental dimension of WM for which waste separation is pivotal.

Unlike the first two models, Models III and IV take a pure environmental stance and emphasize the role of the municipality in waste separation. They both are output-oriented and a municipality is treated as well performing only if it can maximize separated waste collection. With total waste collected being on the input side, this effectively means that a municipality is assessed by its success in waste separation relative to waste generation that it must sustain. The models differ in other optimization criteria that appear as inputs that represent some operating constraints to the municipality. Whereas Model III stresses financial constraints (MSWE), Model IV accounts for potential demand serviced (population, built-up area, and housing units).

Each model sheds some light upon performance of the municipality in waste collection, and since it approaches a production model underlying production of WM service from a distinct viewpoint, it is not proper to speak of efficiency, but rather of performance. Models I – IV come to existence by slicing the production process from different angles in full recognition that identification of a single (perhaps multi-stage) production model in this case, as is in many others, is debatable at best and open to criticism. The models avoid undesirable outputs (e.g., residual non-separated waste), and the performance assessment is based upon radial measures of efficiency to make the methodology compliant with the state of the art (cf. Bădin et al., 2014).[[2]](#footnote-2) Albeit it is possible to incorporate non-desirable outputs and extend measurement in a non-radial direction, the ambition is to pinpoint contextual factors of the operating environment of municipalities that contribute to better performance or hamper it. Even though it is possible to presume that applicability extends *mutatis mutandis* to non-radial models with undesirable outputs, the presently available two-stage approaches lack this theoretical justification and any attempt of the sort would be of a heuristic nature, be that post-hoc regression modelling in the style of Simar and Wilson (2007) or Banker and Natarajan (2008) or full unconditional-to-conditional analysis in the style of Daraio and Simar (2005, 2007).

Of course, the catalogue of production variables is far from being complete. Some studies often include inputs like the number of vehicles or employees engaged in WM service (e.g., García-Sánchez, 2008; Sarra et al., 2017; Salazar-Adams, 2021), but these variables are just another expression of cost items that are considered here in compact form as MSWE. For Czech municipalities these indicators are irrelevant since provision of WM service is typically outsourced and delegated to an external company. In other studies residual (non-sorted, non-spearated) waste is singled out as an undesired output (e.g., Romano and Molinos-Senante, 2020). This variable is actually treated in Models II to IV implicitly in a difference fashion by considering total waste and separated waste as outputs or by placing them on different sides of the production process.[[3]](#footnote-3)

3.2 Potential contextual factors affecting WM performance

Recent literature offers numerous suggestions about potential drivers of performance in MSWM (e.g., Guerrini et al., 2017; di Foggia and Beccarello, 2020). In practice, analysis is typically limited by data availability, which is an issue also in the Czech Republic, where there are long-standing disputes concerning public unavailability of relevant WM data apart from those aggregated at a central or regional level. In consequence, there is no kind of a publicly available central database storing data on WM for a municipal level. Conversations with municipal officials responsible for WM in their municipalities, a review of the extant empirical literature and explorations of available data gave rise to a list of 12 potential factors related to the operational environment of providing WM service. These contextual factors whose effect upon performance might be positive or negative are listed in Table 2 with a brief description and statement of the anticipated influence upon WM performance. The anticipated effect (+, –, +/–) comes either from available empirical literature where these factors were previously studied or from insights intermediated by municipal officials. To the best knowledge of the authors, some of these factors are novel and have not been applied previously in a WM performance analysis. In no manner is it claimed that these factors can be easily disentangled from inputs and outputs. Conversely, some of them are directly related to total or non-separated waste collected, which is properly taken under advisement in the adopted analytical technique. It is also worthwhile noting that the 12 contextual variables vary in terms of their measurement scale including numeric and nominal variables.

Whereas the content and measurement units of contextual variables are displayed in Table 2, the following reasoning applies to their choice and the presumed anticipated influence:

* MSW collection frequency/month (z1): If waste collection occurs more frequently, it is more convenient to customers as less capacity is needed for storing waste between two pick-ups. On the other hand, this typically entails higher costs. Collection frequency varies from four times per month to as low as once per month in municipalities with a biweekly collection schedule alternating non-separated (residual) and green waste. The anticipated effect upon performance is negative (–).
* Bin records (z2): A municipality can keep track of the number of bins for non-separated (residual) waste used in the form annually issued stickers or barcodes. Whilst there is no theory justifying the effect on performance, some municipal officials suggested that with proper records the municipality is billed less by the WM company. Nonetheless, the anticipated effect upon performance is ambiguous (+/–).
* HWRC open per week (z3): Most municipalities (73 %) operate no household waste recycling centre (HWRC)[[4]](#footnote-4) or comparable facility, so this frequency is zero. With an HWRC present, the availability ranges between six days per week to once a month with an average being twice per week. Better availability should result in less waste ending up in residual waste bins, but the price is higher costs. For this reason, it is difficult to determine the anticipated effect (+/–).
* Availability of HWRC free-of-charge (z4)[[5]](#footnote-5): Albeit charging no fee for leaving recyclables at an HWRC or a comparable facility should encourage a higher tendency towards waste separation, the ultimate effect might be in the end marginal as a majority of recyclables are collected through drop-off sites. Hence, the anticipated effect is ambiguous (+/–).
* Separation drop-off sites (z5): Higher availability of sites increases convenience and subsequently an inclination to waste separation, but requires higher costs to operate more sites. Some municipalities with collection of recyclables from individual housing units even do not use drop-off sites at all. Depending on the model, the anticipated effect is ambiguous (+/–).
* Population per separation drop-off site (z6): A lower density of drop-off sites may suggest lowered costs, but also implies lessened convenience for citizens, and in consequence a lower turnover of separated waste. It is therefore difficult to state the anticipated effect (+/–).
* Curbside collection of recyclables (z7): Regardless of whether it is in the form of bins or sacks, curbside collection grants citizens a very high level of convenience and suggests higher willingness to participate in waste separation. Increased costs of source collection are usually compensated by lower costs for less frequent drop-off sites that are no longer needed as previously. Hence, a positive effect upon performance may be anticipated (+).
* Waste separation incentive program (z8): With incentives, people are motivated to separate more assiduously, which results in lower volumes of residual waste and greater volumes of recyclables that are typically much cheaper to treat. Therefore, the anticipated effect is positive (+).
* Green waste collection program (z9): On the one hand, diverting green waste from residual waste is likely to induce savings on account of less residual waste. On the other hand, separate collection of another category of waste generates additional costs. Thus, the anticipated effect is ambiguous (+/–).
* Share of condominium housing units (z10): Municipal officials suggested this type of housing structures to be more problematic for waste collection with a pressure upon costs. Yet, condominiums imply a highly concentrated population and could incur less unit costs as compared to scattered single-family houses. Thus, the anticipated effect is difficult to state (+/–).
* Share of recreational dwellings (z11): Municipal officials generally pinpointed recreational dwellings as more problematic on account of irregular waste generation by their owners and visitors who pay less-caring attitudes. With the result being more frequent littering than elsewhere, the anticipated effect is negative (–).
* Population to built-up area (z12): A higher concentration of people should ease waste collection, and WM should benefit form economies of size. As a result, the anticipated effect upon performance is positive (+).

Table 2: Contextual variables and their expected influence upon MSWM performance

|  |  |  |  |
| --- | --- | --- | --- |
| **Code** | **Contextual variable and brief description** | **Type** | **Expected influence** |
| z1 | **MSW collection frequency/month** (measures how many times per month the WM company collects residual waste) | discrete | − |
| z2 | **Bin records** (indicates whether the municipality keeps any kind of individual bin records) | yes/no | +/− |
| z3 | **HWRC open per week** (measures how many days in a week the HWRC, if present, is open to the public) | discrete | +/− |
| z4 | **Availability of free-of-charge HWRC** (indicates whether citizens pay at the HRWC, if present, for leaving recyclables) | yes/no | +/− |
| z5 | **Separation drop-off sites** (measures the number of sites of recyclables collection within the municipality) | discrete | +/− |
| z6 | **Population per separation drop-off site** (measures how many citizens in the municipality a drop-off site services on average) | continuous | +/− |
| z7 | **Curbside collection of recyclables** (indicates whether the munici­pality provides curbside collection of recyclables to households) | yes/no | + |
| z8 | **Waste separation incentive program** (indicates whether an incentive program for either total waste reduction or increased separation of recyclables is implemented in the municipality) | yes/no | + |
| z9 | **Green waste collection program** (indicates whether green waste, typically garden waste, is collected separately) | yes/partly/no | +/− |
| z10 | **Share of condominium housing units** (measures the proportion of condominium-type housing units to all permanently occupied housing units in the municipality) | continuous | +/− |
| z11 | **Share of recreational dwellings** (measures the proportion of recreational dwellings to all permanently occupied housing units in the municipality) | continuous | − |
| z12 | **Population to built-up area** (measures population density in the built-up (urban) area of the municipality) | continuous | + |

3.3 Assessment of WM performance conditional on contextual factors

The paper employs a non-parametric approach reposing upon data envelopment analysis (DEA) in assessing WM performance of Czech municipalities. To this end, a municipality is in this context considered as a production unit (or decision-making unit) that has autonomy over the use of inputs in producing outputs. The production models adopted for the analysis of MSWM performance are summarized earlier in Table 1. DEA converts each such production model into a linear programming problem that provides simultaneously (i.) an implicit estimate of the production (or rather performance) frontier created as an envelope of the observed production data, and (ii.) an estimate of the distance of a municipality from the estimated production (or performance) frontier expressed as a score. Traditionally, it is assured that this score is limited to the interval (0,1] where the upper limit 1 signifies full (or benchmark) performance. The advantage of DEA over other approaches rests in handling easily multiple inputs and multiple outputs without any specification of a particular functional form relating inputs to outputs. Whereas DEA methodology for simple cases of multiple inputs and multiple outputs is well developed and covers numerous situations that arise in applications (e.g., uncertain data, non-discretionary data, outliers, non-radiality), there is some uncertainty when there are contextual (or environmental) factors at play that may affect performance. These contextual factors capture environmental and operating conditions in which municipalities undertake provision of WM service. Those employed in this study are exposited in Table 2.

As a matter of fact, modeling contextual factors in DEA is an interesting research front, far from being closed (cf. Liu et al., 2016, Subsection 5.1). There are two different responses to contextual factors. One approach is termed two-stage analysis or two-stage DEA, whereas the other may be loosely named unconditional-to-conditional (UTC) analysis. Both these approaches augment the analysis by a second stage that explains the effect of contextual variables. Irrespective of the method, this seems a logical step as it significantly improves the practical usefulness of results, which is supported also by Rogge and De Jaeger (2012). In the words of De Witte and Kortelainen (2013), neglecting the operational environment can make DEA results meaningless.

Two-stage analysis was first used by Ray (1988) and adds to standard DEA a second stage in which performance scores are regressed upon contextual variables. In estimating the regression equation, it is fairly common to deploy ordinary least squares (OLS) or formulate a censored (tobit) regression model (e.g., Hoff, 2007; McDonald, 2009; Simar and Wilson, 2011; Johnson and Kuosmanen, 2012). The truth is that early implementations of two-stage DEA were lacking in theoretical support, in response of which Banker and Natarajan (2008) developed a statistical framework justifying OLS, whilst Simar and Wilson (2007) made a compelling argument in flavor of truncated regression. Finally, Banker et al. (2019) proved superiority of OLS for practical applications. Be that as it may, the use of this kind of two-stage analysis necessitates that contextual variables do not distort the production possibilities set, which is called the separability condition. Daraio et al. (2018) developed an asymptotic framework based on the central limit theorem for testing whether the separability condition holds.

Another approach may be traced to Daraio and Simar (2005, 2007), and its strength is in the irrelevance of the separability condition, which makes it a universal approach in spite of its relative computational burden. The rationale is to compare performance scores computed free of contextual variables (unconditional scores) to those with full account for contextual variable (conditional scores). Unconditional scores relative to conditional scores (UTC ratios) are then non-parametrically regressed upon contextual factors. Unconditional-to-conditional (UTC) analysis is applicable in a traditional manner with the use of so-called full frontiers, or robustified with the use of so-called partial frontiers. Whereas the idea of the former is to use all observations as they are observed, the latter utilizes only a fraction of observations in a repetitive bootstrap fashion so as to establish resistance against outlying observations. The latter is based upon order-*m* efficiency developed by Cazals et al. (2002) or order-α devised by Aragon et al. (2005).

Although in studies on WM performance two-stage DEA, and specifically the double-bootstrap procedure formulated by Simar and Wilson (2007), is proliferated (e.g., Simões et al., 2010, 2012a; Benito-López et al., 2011), it hinges on separability of contextual factors from production, which is not supported in this present analysis. For this reason, the following concise exposition is devoted to UTC analysis, which may proceed in two variants, depending on whether it applies the concept of order-*m* or order-α efficiency. Example WM studies based on UTC analysis are listed by Ferreira et al. (2020) or Simões et al. (2012a). UTC analysis sets up partial frontiers models that do not envelop the entire sample and are thus less sensitive to the presence of outliers, whilst being adjustable to inclusion of contextual variables that render the results conditional. An application of order-*m* frontiers requires that the parameter *m* is specified by stating the number of peers against which performance is matched in bootstrap simulations, whilst order-α frontiers need the value of α that is the probability that a point outperforms the frontier. There is a correspondence between *m* and α, but order-*m* frontiers in spite of their greater fragility to outliers are statistically more efficient (Daouia and Gijbels, 2011). This paper uses order-*m* frontiers in juxtaposition with full frontiers.

On the one hand, empirical studies that prefer two-stage analysis in the spirit of Simar and Wilson (2007) use radial efficiency scores under the convexity assumption imposing variable returns to scale, which aligns the analysis with the BCC (Banker – Charnes – Cooper) model of Banker et al. (1984). On the other hand, studies that prefer UTC analysis work only with the assumption of free disposability and they effectively use the FDH (free disposal hull) estimator of Deprins et al. (1984). Examples of such studies focusing upon WM performance are Ferreira et al. (2020) or Simões et al. (2012a), and similar such studies from different fields are De Witte and Kortelainen (2013) or Cordero et al. (2015, 2017). Certainly, variable returns to scale are a desirable requirement since municipalities vary in size, and this operating requirement entails that there is no constant effect with increasing size, but rather some variability in scale effects. Application of variable returns to scale when evaluating MSWM performance is also suggested by Callan and Thomas (2001).

The technicalities to come presume that WM performance of a municipality  is represented by a triple , where  are inputs,  are desirable outputs, and  are contextual variables. Such data are available for all *n* municipalities, so the analysis is based on a sample , where  is the index set encompassing allmunicipalities. Isolating the effect of contextual variables  from WM service represented by  and  requires conditioning  upon , and practical implementation necessitates some notion of vicinity around a particular observation of . Cazals (2002), Daraio and Wilson (2005, 2007) proposed smoothing the density of  by a suitable kernel function  with bandwidth vector  and bounded support.[[6]](#footnote-6) With this in hand, conditioning on a particular value  is attained by selecting those municipalities that do not deviate by their contextual variables from  by more than . To that end, a conditioning index set is defined .

*Full frontiers.* When all observations in  are used simply as they are, a full frontier is constructed. The assumptions of free disposability and convexity yield a traditional input-oriented DEA estimator of efficiency score in the form

|  |  |
| --- | --- |
| , | (1) |

whose value is known as a BCC efficiency score (or as an input-oriented Debreu-Farrell efficiency score under variable returns to scale). Conditioning on contextual factors  implies virtually that this optimization is run only for those municipalities that are close to  and are in the index set . Hence, a conditional input-oriented DEA estimator with a full frontier emerges from the linear program

|  |  |
| --- | --- |
| . | (2) |

*Partial frontiers.* In an attempt to obtain robust counterparts to  and , partial frontiers are constructed by considering only a fraction of municipalities that are then used in estimating efficiency. For order-*m*, there are *m* such municipalities that are drawn randomly from  without replacement (*m* is an integer, possibly greater than *n*).[[7]](#footnote-7) Since any *m*-tuple generates its own particular estimate, the procedure is run as Monte Carlo simulations, and the results are then averaged to approximate the underlying expectation. An order-*m* input-oriented DEA estimator yields an efficiency score by using the program

|  |  |
| --- | --- |
| , | (3) |

where  the order-*m* input efficient level for municipality  estimated by the FDH estimator. Daraio and Simar (2005, p. 103) recommend estimating  by running a sufficient number of *B* simulations (with a typical value of *B* in applications set to 2,000) under this algorithm:

1. For a given  select those municipalities  for which , and draw a sample of size *m* with replacement from this selection. This results in a sample .
2. Compute .
3. Iterate over steps 1 and 2 a total of *B* times.
4. Set finally .

All in all, the estimation procedure starts with projecting inputs upon the frontier estimated by FDH, , and ends with running otherwise standard linear program (3) with FDH projections of inputs substituted for observed values of inputs. A similar Monte-Carlo algorithm is available in the conditional version. A conditional order-*m* input-oriented DEA estimator answers to this algorithmic procedure:

1. For a given  select those municipalities  for which , and draw a sample of size *m* with replacement and a probability commensurable with . This results in a sample .
2. Solve the linear program

|  |  |
| --- | --- |
| , | (4) |

1. Iterate over steps 1 and 2 a total of *B* times.
2. Set finally .

*Other orientation.* The estimation of unconditional and conditional scores according to the described procedures must be executed separately for each  in . Furthermore, the preceding presentation focuses upon an input-oriented case, and the formulas can be modified with ease to an output-orientation, but it must be assured that output-oriented scores are restricted to the [0,1] range as well.

*Testing separability.* Separability means that contextual variables have a zero impact upon the production possibility set.[[8]](#footnote-8) In order to test separability, Daraio et al. (2018) exploited the central limit theorem to compare the level and variability of unconditional and conditional efficiency scores in constructing two non-parametric test statistics with a limiting standard Gaussian distribution. The test statistics are implemented with partial frontier and correct for bias, having a general familiar format , where  and  are estimators of the mean values of unconditional and conditional efficiency scores, and  and  are estimators of their respective standard errors. The term  is a bias correction for bias that arises in the estimation of unconditional and conditional efficiency scores. Under the null hypothesis of separability, the unconditional and conditional frontiers collapse, and there is thus no difference in the estimated unconditional and conditional scores save some statistical variation. Both test statistics are implemented as a right-tailed test and their simple definitional structure requires that unconditional and conditional estimators are applied to different subsamples. In other words, to suppress correlation that would arise if the same sample were employed in unconditional and conditional estimations, the data must be split into two sufficiently large subsamples for which estimations are applied independently. The T1 test is applicable for , and the T2 is justified for .

*Testing the effect of contextual variables.* Unconditional scores capture gross performance and conditional scores describe performance net of contextual factors. UTC analysis further explores the effect of contextual factors on the production process by exploring how the contextual factors are linked with unconditional-to-conditional-measures ratios that are defined as

|  |  |
| --- | --- |
| and , | (5) |

for the full frontier case and for the order-*m* partial frontier case. The key difference is that the full-frontier ratio  is more exposed to outliers and less robust than the partial-frontier ratio . Daraio and Simar (2005) and Bădin et al. (2014) recommend explaining these ratios in a regression manner by running a non-parametric regression of  upon  and/or . Kernel-based approaches were originally thought of by these authors and these are also applied in empirical analyses to smooth all contextual variables (e.g., Simões et al., 2012a; De Witte and Korteilanen, 2013; Cordero et al., 2015; Ferreira et al., 2020). In point of fact, any smoothing technique allowing visualization and significance testing is acceptable. To that effect, a generalized additive model (GAM) is employed in this paper that may take the following format for the full frontier case

|  |  |
| --- | --- |
| . | (6) |

This representation recognizes that some contextual variables are nominal, , whereas others are numeric, (where ). The four terms in formula (6) represent an intercept, a parametric part for nominal variables, a non-parametric part for numeric variables, and an error term, respectively. Nominal variables are appropriately recoded to dummy variables  with 1/0 values for “yes”/”no” answers, and  are regression parameters corresponding to “yes” answers. If a nominal variable takes more than one value (e.g., “partly” as is the case of z9), more levels are needed and the parametric part in formula (6) must be adjusted accordingly. The parametric part is composed additively of contextual variables smoothed by splines . The GAM in formula (6) is fitted for each model and for both full and order-*m* partial frontiers by using the local scoring algorithm based on backfitting used in a standard iterative fashion. For partial frontiers,  is simply replaced by . A graph of trajectories of smoothed values  against original values  displays how UTC ratios vary with, and are affected by, contextual variables. The framework also allows standard significance testing. Useful details on GAMs are available, e.g., in Hastie and Tibshirani (1990) or Madsen and Thyregod (2011). A UTC ratio greater than 1 indicates that the local environment of a municipality exerts detrimental operating conditions for efficiency because the conditional efficiency score (answering to a hypothetical situation that the environmental context does not matter) is better than the unconditional efficiency score (inclusive of environmental effects). Hence, an increasing trend of  testifies of detrimental effects of contextual variable  on efficiency, and a decreasing trajectory of  points to a negative influence. Needless to say, the effect of a contextual variable need not be monotonic and may vary across the range of its values.

3.4 Data on Czech municipalities in the South Moravian Region

The Czech Republic has one of the highest municipal fragmentations in Europe, and thus a typical Czech municipality is rather small, although not precisely rural since they are usually located relatively close to each other. To a certain extent, the conglomerate form of a spatial scatter is a relic of the previous Communistic regime that significantly limited independence of municipalities. Nonetheless, the change of the regime with municipalities gaining independence stirred a very strong reluctance towards any kind of municipal amalgamation. With such a type of municipal structure, this analysis provides an interesting contribution to the available literature on MSWM performance.

The analysis reposed upon a data set of 470 municipalities from the South Moravian Region that otherwise consists of 673 municipalities with a total population of almost 1.2 million inhabitants with the regional capital city Brno (a population of 380,000 inhabitants). Other municipalities in the South Moravian Region are substantially smaller in size with the second largest having a population of 34,000 inhabitants, and only four more having more than 20,000 inhabitants. All remaining municipalities have a population under 12,000 inhabitants. With this in mind, due to the significant differences in size compared to the rest of the sample, the regional capital Brno was excluded from the sample at the onset. The reason being, MSWM service in such a highly populated municipality shows notable differences from the rest of the sample as Brno has much wider possibilities for service optimization and also tends to provide a wider range of services than an average small municipality. In spite of adopting the convexity assumption in the DEA estimation, including Brno would render the sample less homogeneous and Brno would appear as and outlier with potentially distorting effects on the estimated frontier. The data set refers to the year 2012. This year was chosen specifically for being the closest year to the last available census that took place in 2011 (with census data being published gradually in the following years), and thus provided detailed data about municipal characteristics, otherwise not regularly collected. Additional statistical data were obtained from databases of the Czech Statistical Office, Ministry of Finance of the Czech Republic, and Ministry of the Environment of the Czech Republic. The final part of the data related to MSWM in individual municipalities was collected directly by contacting their officials using a combination of an electronic questionnaire, personal visits and direct phone calls. Data availability and municipal responsiveness resulted in sufficient and reliable data for 470 municipalities.

Appendix A displays basic statistics of the municipal data considered as inputs, outputs and contextual variables. As was emphasized earlier, the most important factor for Czech municipalities is their expenditure on MSWM. This expenditure, MSWE, is expressed in the Czech currency “koruna” (CZK) and includes total operational cost spent on provision of WM service in individual municipalities. Since small municipalities generally do not run their own WM service, these include payments to an external WM company for waste collection, transport and treatment of both residual and separated waste. If an HWRC is present in the municipality (typically in municipalities over 1,000 inhabitants), MSWE include these costs as well. Owing to their typical small sizes, very few Czech municipalities run their own municipal WM service, and resort to outsourcing from an external company. Outsourcing is the most common way of securing WM service, and this observation accords with that of Bel et al. (2010). If the municipality runs its own WM company, MSWE includes cost for personnel, collection equipment, and other cost related to the provision of WM service, which yields a metric directly comparable with the lump sum that would be paid to an external WM company.

Three variables are proxies for municipality size, and include population size, covered built-up (urban) area and housing units. Unlike the majority of available research (e.g., Simões et al., 2012; Rogge and De Jaeger, 2012; Pérez-López et al., 2021), this study prefers built-up municipal area instead of total municipal area. Built-up area normally accounts for only a few percent of total area and excludes uninhabited surface areas like lakes, fields, forests, or meadows. Built-up area is a better proxy for inhabited surface area. Especially in municipalities with a low population size these two areal metrics tend to differ greatly. These three metrics of municipality size were applied as inputs (in Models I and II) or outputs (in Model IV) simultaneously since a single measure might not always be able to capture properly the scope of the provided service in the presence of disparities in population, built-up area and housing units as indicators of demand. Municipalities differ in population density, the consequence being that one variable is not capable of capturing size effects. To illustrate the extent of municipal fragmentation in the Czech Republic, almost three quarters of municipalities in the data set have less than 1,000 inhabitants and less than 300 housing units.

In terms of separated waste, standard types of waste that were commonly collected in 2012 using drop-off sites and HWRCs are taken into account. Separately collected waste fractions included paper and cardboard, plastics, and glass as main categories, and waste electric and electronic equipment (WEEE), metals, biodegradable waste (typically garden waste) and bulky waste[[9]](#footnote-9) on a smaller scale. All summed with residual municipal solid waste, total municipal waste is obtained. For the sake of clarification, neither commercial waste nor industrial waste is considered in any form in this study, as according to the Czech law commercial subjects are responsible for handling their waste on their own. Hence, only with very rare exceptions are municipalities involved in this process, and generally they have no expenditure incurred in relation to these waste categories.

**4. Results and discussion**

The analysis was conducted in entirety in program R (R Core Team, 2020) with the help of functionalities of packages frontiles (Daouia and Laurent, 2013), gam (Hastie, 2019), np (Racine, 2020), rDEA (Simm and Besstremyannaya, 2020). Most basal procedures demanded of the authors to prepare their own scripts.

The assessment of performance in MSWM was implemented both for full frontiers at the expense of lessened robustness and for order-*m* partial frontiers in the hope of enhancing credibility. For partial frontiers, the value 150 for *m* was chosen in accordance with the notes in Footnote 7 since around this threshold the number of super-efficient firms stabilized for each of the four models. The value for the order-*m* depends on the data set at hand and is by no means unreasonable.[[10]](#footnote-10) In bootstrapping requisite for computations of conditional score estimates or the testing for separability, 2,000 bootstraps were always used. The selected bandwidths of contextual variables are Table 3.

Table 3: Bandwidths selected by least squares cross-validation

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | z1 | z2 | z3 | z4 | z5 | z6 | z7 | z8 | z9 | z10 | z11 | z12 |
| Bandwidth | 0.942 | 0.145 | 0.919 | 0.047 | 4.038 | 147.67 | 0.075 | 0.020 | 0.017 | 0.046 | 0.103 | 15.307 |

Notes: Bandwidths were estimated by the cross-validation method developed by Li and Racine (2008) and Li et al. (2013).

The first-stage results are presented in the summarized form of Table 4, the results of testing for separability is reported in Table 5, and some information is transferred to Appendix B. Table 4 presents and juxtaposes statistical descriptives for unconditional scores (inclusive of the impact of the operating environment), unconditional scores (hypothetical if the operating environment exerted neutral effects), and UTC ratios. Table 5 presents the bootstrap results of the T1 and T2 separability tests according as the inequality conditions were met. Appendix B presents Spearman correlation coefficients between the performance scores and UTC ratios that provide simple measures of congruence or disparity. Whilst for individual municipalities detailed results broken down at the municipal level would be of relevance, of concern to this paper are two questions. A first question is whether there are differences in the assessments provided by the four models, each applying a different viewpoint on MW performance. A second question is whether WM performance is globally affected by contextual factors, either favorably or unfavorably.

First of all, Table 5 reveals that contextual variables in each model are not separable from the production technology and that the operating conditions do affect performance in a measurable sense. The results argue convincingly that conditional scores should be examined if performance is to be reviewed at the level of individual municipalities and be fair to them. The relatively large sample of municipalities in this case should assure that the asymptotics of these tests is valid.

Table 4 confirms clearly that partial frontiers should be preferred over full frontiers, and that there are differences across the perception of MW performance by the models. As to the first point, the number of fully performing municipalities with unit conditional scores is high for each model definitely with full frontiers and also to some degree for Models II and IV with partial frontiers. These situations are attributable to low discriminatory power, which may happen for various reasons (e.g., Simar, 2003; Podinovski and Thanassoulis, 2007), and it is especially conditional scores that are plagued by this property of DEA. Furthermore, with partial frontiers there are numerous super-efficient municipalities with scores greater than 1, which yet provide a better ranking in terms of performance for the second stage as they differentiate municipalities that would otherwise receive a unit score. All these are unmistakeable signs of lesser robustness of full frontiers (i.e. traditional full-sample DEA). Nonetheless, for Model IV there is a high incidence of unit conditional scores with partial frontiers, which is obviously a structural legacy of its chosen input-output set. Regarding the second point and for partial frontiers, there are some regularities manifested in scores and UTC ratios, which are discernible in their distribution (reflected especially in means, medians and ranges). The main finding is that, in general, local operating conditions of municipalities are conducive to MW performance granted that this is perceived through the prism of Models I and II (UTC ratios smaller than 1). Vice versa, operating conditions are found detrimental to performance under Models III and IV (UTC ratios greater than 1). In respect of the economic interpretation of the models explained in and around Table 1, this pattern has these two implications:

* (Models I and II) An average Czech municipality benefits from the adopted organization of MW service (contextual variables z1 – z9) and urban factors (contextual variables z10 – z12) in minimizing its expenditure whilst providing MW service to its citizens. Since urban factors such as land-use structure or population density are outside actual control, Czech municipalities seem to exploit organizational factors of waste collection in securing MW service (assigned and prescribed by law) at a minimum of expenditure. In addition, as the chief distinction between Models I and II is waste separation, an average Czech municipality worsens in MW performance when waste separation is added as another criterion (average unconditional score 0.544 for Model II v. 0.677 for Model I), but it certainly enjoys favorable organizational and urban conditions (average UTC ratio 0.753 for Model II v. 0.566 for Model I).
* (Models III and IV) Discretionary organizational conditions (contextual variables z1 – z9) and urban factors (contextual variables z10 – z12) are to the detriment of an average Czech municipality in maximizing waste separation. The second stage later separates the role of organizational and urban factors. Nonetheless, as Models III and IV differ in the qualification of inputs, it is obvious that an average Czech municipality performs better in waste separation relative to its expenditure on MW service than relative to criteria of potential demand represented by population, built-up area, housing units (average unconditional score 1.419 for Model III v. 0.730 for Model IV), and this appraisal is negligibly affected by operating conditions (average UTC ratio 1.442 for Model III v. 1.392 for Model I).

Simply speaking, waste separation is not a singularly strong point of Czech municipalities, but they stand out in configuring and organizing waste collection to minimize their expenditure on MW service.

Table 4: Descriptive statistics of conditional and unconditional performance scores and UTC ratios yielded by different input-output specifications and frontier delineations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Mean | Standard deviation | Median | Minimum | Maximum | # of unit cases |
| Model I |  |  |  |  |  |  |
| Unconditional score (full) | 0.504 | 0.175 | 0.485 | 0.091 | 1.000 | 8 |
| Conditional score (full) | 0.944 | 0.123 | 1.000 | 0.328 | 1.000 | 357 |
| UTC ratio (full) | 2.089 | 0.839 | 1.927 | 1.000 | 10.986 | 8 |
| Unconditional score (partial) | 0.677 | 0.397 | 0.616 | 0.003 | 2.865 | 7 |
| Conditional score (partial) | 0.597 | 0.320 | 0.559 | 0.003 | 2.060 | 7 |
| UTC ratio (partial) | 0.566 | 0.288 | 0.542 | 0.003 | 1.741 | 7 |
| Model II |  |  |  |  |  |  |
| Unconditional score (full) | 0.528 | 0.185 | 0.502 | 0.121 | 1.000 | 14 |
| Conditional score (full) | 0.957 | 0.109 | 1.000 | 0.375 | 1.000 | 375 |
| UTC ratio (full) | 2.018 | 0.738 | 1.895 | 1.000 | 8.252 | 14 |
| Unconditional score (partial) | 0.544 | 0.270 | 0.522 | 0.003 | 1.562 | 7 |
| Conditional score (partial) | 0.811 | 0.353 | 0.866 | 0.003 | 3.431 | 30 |
| UTC ratio (partial) | 0.753 | 0.281 | 0.814 | 0.003 | 1.880 | 39 |
| Model III |  |  |  |  |  |  |
| Unconditional score (full) | 0.456 | 0.214 | 0.438 | 0.002 | 1.000 | 9 |
| Conditional score (full) | 0.880 | 0.230 | 1.000 | 0.012 | 1.000 | 338 |
| UTC ratio (full) | 3.588 | 19.398 | 1.892 | 1.000 | 41.470 | 12 |
| Unconditional score (partial) | 1.419 | 0.611 | 1.329 | 0.547 | 7.820 | 7 |
| Conditional score (partial) | 1.424 | 0.523 | 1.329 | 0.617 | 6.617 | 7 |
| UTC ratio (partial) | 1.442 | 0.466 | 1.354 | 0.675 | 5.451 | 7 |
| Model IV |  |  |  |  |  |  |
| Unconditional score (full) | 0.454 | 0.210 | 0.440 | 0.002 | 1.000 | 15 |
| Conditional score (full) | 0.883 | 0.225 | 1.000 | 0.012 | 1.000 | 342 |
| UTC ratio (full) | 3.655 | 19.435 | 1.906 | 1.000 | 41.470 | 17 |
| Unconditional score (partial) | 0.730 | 0.269 | 0.784 | 0.003 | 1.479 | 46 |
| Conditional score (partial) | 0.718 | 0.266 | 0.761 | 0.003 | 1.297 | 54 |
| UTC ratio (partial) | 1.392 | 0.819 | 1.273 | 0.439 | 11.967 | 7 |

Notes: For partial frontiers, the choice of *m* = 150 was adopted. The last column, # of unit cases, states the number of fully performing municipalities (for unconditional or conditional scores) or the number of municipalities where the local operating environment does not alter performance (for UTC ratios).

Municipalities with unit unconditional scores for full or partial frontiers whose counts are given in the last column of Table 4 are best performers. They are relatively diverse with no significant feature that would distinguish them from the rest. They include municipalities that vary vastly in size, have various waste collection frequencies and MSWE per capita comparable to others. They outstand from others in significantly higher-than-average collected recyclables per capita, together with a higher-than-average share of collected recyclables on total generated municipal waste.

Table 5: Results of the separability tests

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Model I | | Model II | | Model III | | Model IV | |
| T1 test | T2 test | T1 test | T2 test | T1 test | T2 test | T1 test | T2 test |
| Statistic | -36.927 | -23.281 | NA | -9.839 | -13.205 | NA | NA | -7.783 |
| Significance | 0.000***\*\*\**** | 0.000***\*\*\**** | NA | 0.000***\*\*\**** | 0.000***\*\*\**** | NA | NA | 0.000***\*\*\**** |

Notes: The T1 test is applicable wherever the number of inputs, *p*, and the number of outputs, *q*, satisfy the inequality 2/(*p* + *q* + 1) ≥ 0.40. Likewise, the T2 test is established for cases when 2/(*p* + *q* + 1) < 0.50. If neither test is applicable, this is indicated by NA. The significance label ***\*\*\**** answers to a p-value ≤ 0.001.

With different models applied, a traditional enquiry is whether there is some similarity between unconditional scores, conditional scores and UTC ratios, and whether they yield comparable information. Yet, by reason of a complicated and intractable mathematical structure of scores stemming out of even basic DEA models with different input-output configurations, there is no need to presume relationships of a linear format. Therefore, for both full and partial frontiers, Appendix B reports Spearman correlation coefficients instead of commonly employed Pearson correlation coefficients. Pair-wise relationships in the case of non-robust full frontiers are somewhat erratic as opposed to partial frontiers with more systematic patterns. The unsteadiness of correlations with full frontiers results from the truncation of scores from above by one. A meaningful ranking of municipalities is sabotaged by the occurrence of numerous unit conditional scores. Hence, it is sensible only to review the case of partial frontiers. There is universally a high degree of congruence in the scores and UTC ratios of Models I, II and III, or even between Models I and II. In these cases Spearman correlations are greater than 0.885. In contrast, there are regular inverse patterns of assessment between Models I and III as well as between Models II and III with Spearman correlation coefficients ranging from -0.633 to -0.227, suggesting thus a tendency to an opposite ranking. Diverse patterns with more harmonious and discordant rankings are within Model IV and between Model IV and any other model, which follows from a higher proportion of unit unconditional and conditional scores (46 and 54 cases, respectively). All things considered, Models I and II are very similar in terms of assessments and dissimilar from Model III. The reason being, the input-output configurations of Model I and II are alike and they follow an input orientation. Model III is output-oriented with an altogether modified input-output set. Hence, Models III and IV inspect MW performance from a different angle than Models I and II do.

In the second stage of the analysis UTC ratios were regressed upon contextual variables in a GAM framework for either frontier and for each of Models I – IV, yielding thus 2 × 4 = 8 regressions. Each fit obeyed the same specification schematically described by equation (6). The “yes/no” and “yes/partly/no” factors z2, z4, z7, z8 and z9 were included in the parametric part of the model, whilst the discrete and continuous numeric factors z1, z3, z5, z6, z10, z11 and z12 were cast into the non-parametric part and smoothed. For partial frontiers, Appendix C reports fitted smoothed trajectories (variables z1, z3, z5, z6, z10, z11 and z12) or estimated regression coefficients (variables z2, z4, z7, z8 and z9) endowed with approximate 0.95 confidence bands. Regression coefficients corresponding to nominal answers “yes”, “no” and “partly” are displayed at 0, 1 and 0.50 (only for z9). In order to enhance the portrayals in Appendix C, original values 0, 1 and 0.50 (only for z9) were slightly jittered to avoid concentration in just one stick on the horizontal axis. Jittering was applied only for nominal variables. Smoothed paths and their upward or downward sloping trends give an indication of the effects of numeric contextual variables upon performance, whilst levels of estimated regression coefficients have a similar use for nominal variables. For the sake of visual inspection, as long as a horizontal line can pass trough the confidence bands, no effect is detected for the variable in question and its insignificance is established. Table 6 reports the results of a formal assessment of significance grounded on a score test as well as R-squared measures associated with the fits. For ease of reading, Table 6 displays significance labels only and do not report p-values. Lower R-squared values with some fits may be unsettling, but these are not an issue in the present analysis as it is generally conceded that in the second stage one cannot expect to have a high R-squared. Here, applicable for UTC ratios as well, Sarra et al. (2017) note that DEA scores are mainly determined by the internal organization of the production process, and external variables then account only for small fractions attributable to operational variables not controlled by the municipality. Nevertheless, knowledge about municipal characteristics and environmental factors that are significant for MW performance are inevitably helpful to the municipality. This knowledge is invaluable primarily for controllable contextual variables (z1 – z9) as these constitute indirect drivers of performance.

Table 6: Results of the second-stage non-parametric regressions of UTC on contextual variables

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | Model I | | Model II | | Model III | | Model IV | |
| Full frontier | Partial frontier | Full frontier | Partial frontier | Full frontier | Partial frontier | Full frontier | Partial frontier |
| z1 |  |  |  |  |  |  |  |  |
| z2 | • |  | \* |  |  |  |  |  |
| z3 | \*\* | \*\*\* | \*\*\* | \*\*\* |  | \*\*\* |  | \*\*\* |
| z4 | • |  | \* |  |  |  |  |  |
| z5 | \*\*\* | • | \*\*\* | \*\* |  | \*\*\* |  | \*\*\* |
| z6 | \*\*\* | \*\* | \*\*\* | \*\* |  | \*\*\* |  | \*\* |
| z7 |  | • | • |  |  |  |  |  |
| z8 |  | \*\*\* |  | \*\*\* |  | \*\* |  | \*\*\* |
| z9 |  | \*\* |  | \*\* |  | \*\*\* |  | \*\*\* |
| z10 | • |  | • |  |  |  |  |  |
| z11 | \*\*\* |  | \*\*\* | \* |  | \*\* |  | \* |
| z12 | \*\*\* |  | \*\*\* |  |  |  |  |  |
| R-squared | 0.415 | 0.171 | 0.445 | 0.215 | 0.125 | 0.221 | 0.122 | 0.218 |
| Observations | 470 | 470 | 470 | 470 | 470 | 470 | 470 | 470 |

Notes: Asterisks and dots indicate statistical significance derived from p-values following this notational norm: \*\*\* p-value ≤ 0.001, \*\* p-value ≤ 0.01, \* p-value ≤ 0.05, • p-value ≤ 0.10. For partial frontiers, the choice of *m* = 150 was adopted.

In point of fact, in what follows, only the results for partial frontiers are heeded and interpreted, which comes at no loss of insight since the visualizations for full frontiers are much alike to those for partial frontiers organized in Appendix C. Discernible differences appear only in the p-values reported in Table 6, but these are a consequence of different inferential procedures. Reconciling the results in Table 6 and Appendix C, the findings are fairly uniform across all the four models (for partial frontiers). It should be recalled that a statistically significant upward (downward) smoothed trajectory of a contextual variable displayed in Appendix C testifies of a detrimental (favorable) impact upon municipal performance in MW service. Significance is statistically evaluated at a significance level of 0.05 using the report of Table 6. The contextual variables z1, z2, z4, z7, z10 and z12 are not found significant for MSWM performance, the effect of z3 and z5 is positive, the effect of z6 varies non-monotonically, the effect of z8, z9 and z11 is negative.

* MSW collection frequency (**z1**) was found of no significance upon MSWM performance. Likewise, De Jaeger et al. (2011) did not discover any significant effect of a varied collection frequency for Flemish municipalities in spite of remarkable sociodemographic differences between Flemish and Czech municipalities (e.g., triple population density, much flatter terrain, more-than-tenfold larger average municipality). That said, during interviews officials of Czech municipalities that had decided to decrease the waste collection frequency always observed a significant decrease in MSWE in exchange for typically only a little decrease in the convenience of inhabitants. However, such a decision requires a certain level of political “bravery” and an ability to explain people that benefits will prevail over negatives. In consequence, the absent effect of waste collection frequency implies that unless the convenience of inhabitants lags behind the pressures of a tight municipal budget and dominates amongst the policy goals, it is counterproductive for a municipality to accelerate waste collection as the achieved effect upon MSWM performance would be on average nil.
* Residual waste bin records (**z2**) through issued stamps, stickers or barcodes attached to bins proved to exert an insignificant effect on MSWM performance. Whilst there was usually no kind of limitation as to how many bins a dwelling can have, once bin records were instituted, several municipal officials reported a sudden drop in bin numbers billable by the WM company, even though they observed no or only a marginal visual change in the number of bins through the municipality. This might imply overbilling in the past. Moreover, various municipal officials argued that with a records system some people often voluntarily gradually started using fewer fully stuffed bins instead of multiple partially filled bins. In spite of this reported experience, keeping detailed residual waste bin records does not seem ultimately linked with MSWM performance. Appealing as it may be at first sight, the results in this particular case provide no justification for the municipality to maintain data about the number of residual waste bins. On the one hand, keeping track of the available capacity helps the municipality to make better arrangements with the WM company and eventually to negotiate savings conditional on the type of billing. On the other hand, this poses a further clerical burden on the municipality without any proven benefit for MSWM performance.
* Operating days of an HWRC per week (**z3**) were found positively related to MSWM performance. The more days the HWRC is open, the higher performance the municipality on average attains. With institutional and technical support provided by HWRCs in waste separation, inhabitants are more prone to separate, and produce in turn less residual waste, which eventually generates savings in MSWE. Even though running an HWRC incurs some costs, the benefits seem to prevail as indicated by municipal officials. Such an HWRC may not be necessarily operated at no cost for citizens, but availability of a free-of-charge HWRC (**z4**) was not proven to be of a statistically significant effect. Nonetheless, for a small municipality these findings do not provide useful advice as an HWRC is only present in very large municipalities (not only of the South Moravian Region, but also in the entire Czech Republic) and smaller municipalities find it costly to operate when compared to potential benefits. But as long as an HWRC is present, it should be ideally open as frequently as possible (not necessarily for long hours) in order to improve availability to the public and encourage waste separation in the end.
* Drop-off sites were found statistically significant for MSWM performance. Whereas the number of separation drop-off sites (**z5**) were observed positively correlated with MSWM performance, density of drop-off sites (**z6**) exhibited a non-monotonic pattern. With a lower level of density with up to about 600 people per site, the effect upon MSWM performance is positive, but after this threshold the positive effect evaporates or turns slightly negative. Drop-off sites represent the most common way of waste separation in the Czech Republic and are practically mandatory in every municipality. These results suggest that MSWM performance is generally increased by availability of drop-off sites. A municipality should operate as many drop-off sites as possible to improve in its performance, and there is a sort of limit for the number of drop-off sites. If drop-off sites are too sparse relative to population size, this may have in the end a negative effect, or none at best. The hockey-stick pattern in the plots for z6 in Appendix C indicates that the optimal value is about 600 people per drop-off site. Of course, the observation that municipalities with a denser network of drop-off sites promote separation amongst citizens as they are closer to them is not novel (González-Torre and Adenso-Diaz, 2005; Struk, 2017). All this furnishes policy makers with the need to optimize the number of drop-off sites. In general, availability of drop-off sites is propitious to WM performance, but their availability to the public must be optimized. Too sparse or too dense networks of drop-off sites are in fact unfavorable. Municipalities should examine marginal effects of additional drop-off sites on the scale of cost and separation increase. Irrespective of the outcome of such an analysis, the threshold of about 600 people per site is applicable for an average municipality.
* No significance for MSWM performance was affirmed for curbside collection of recyclables (**z7**). These results are not consistent with previous research that observed a positive effect of curbside collection (e.g., Salazar-Adams, 2021). In contrast, multiple studies focusing on the environmental impact of this measure claim a significant increase in the amount of collected recyclables of sometimes over 50% or even 100% once property-close (curbside) collection of recyclables was launched (e.g., Folz, 1991; Dahlén and Lagerkvist, 2010; Struk, 2017; Guerrini et al., 2017). This increase in waste separation was observed in this case as well, albeit at the expense of a higher MSWE that in the end offset gains in MSWM performance. Overall, curbside collection of recyclables represents usually a very convenient type of waste separation system for people, and multiple studies identified it as one of the most important determinants whether to separate waste or not. Yet, the benefits in one area coincide with the costs in another, resulting thus in a neutral end effect upon MSWM performance. The reasons can be perhaps traced to the attitudes or demeanor of citizens who may not be accustomed to this method of recyclables collection. Municipal officials also pointed out that it often takes several years to fully exploit the potential of this measure, and this method of collection might have been relatively new to municipalities in the South Moravian Region in 2012. A promotional program supported with a reasonable campaign might be a viable avenue for municipalities to encourage acceptance of this service and nudge them to more disciplined separation. This does not come without risks since if this campaign is not handled properly, it might take quite a long period for people to adjust their behavior, whilst for the municipality the dominant effect would be increased costs. In some cases this transitional period might be excessively long for the municipality to bear.
* In addition to curbside collection, some municipalities have adopted a waste separation incentive or green waste collection program (**z8**, **z9**). Both these instruments were found to bear harmfully upon MSWM performance. Under the former, citizens are able to get discounts on the waste collection fee or some other benefits, which should motivate their willingness to separate, generate savings on MSWE and increase MSWM performance. Yet, the effect is detrimental, which ensues likely from the fact that cost reduction associated with decreased residual waste generation cannot make up for additional costs of adopting a separation incentive program. This is at variance with significance of such incentive schemes for sustainable performance advocated by Hornik et al. (1995), Schultz et al. (1995), and more recently by Sidique et al. (2010), Bucciol et al. (2015) or Struk (2017). On the basis of these observations, if the chief concern of municipalities is cost reduction without collateral goals, adopting of an incentive program is not advisable for it will certainly increase MSWE and future benefits are difficult both to gauge and to predict. Yet, this stern refusal of any kind of an incentive program may not be defendable if the municipality is eligible to receive government support in the form of rewards (e.g., from EKO-KOM) if it meets a pre-set waste separation level. Under a green waste collection program, citizens have an option to collect separately green waste (especially from gardens). If utilized to a full extent, benefits are in a smaller amount of solid waste and residual waste in particular. Here the estimated effect is significantly negative, which simply means that in the 19.4 % municipalities that implement a green waste collection program, citizens avail themselves of this option only marginally and the net effect on MSWE and elsewhere is unfavorable. This pattern may also be due to the fact that the examined data date to the year 2012, and in some municipalities separate garden waste collection has only started. In this regard, representatives of several municipalities that had adopted this measure prior to 2012 voiced the prognosis that this process usually takes time and actual benefits of this measure tend to fully emerge only after several years. Indeed, general statistics after the mandatory introduction of garden waste separation in the Czech Republic in 2014 confirm a growing share of garden waste on municipal waste. The findings do not permit to draw firm policy implications in this regard. Certainly, green waste collection is suited for municipalities with areas dominated by single-family houses with large gardens as well as for rural municipalities, where diverting green waste from residual waste to special waste bins can bring sizeable benefits. Only modest benefits can be anticipated for municipalities with a significant part of housing structures consisting of multi-family houses with small gardens and condominiums.
* Share of condominium housing units (**z10**) was found insignificant, whereas share of recreational dwellings (**z11**) was found significant and negatively correlated with MSWM performance. Municipal officials surmised that concentration of condominiums should run counter to MSWM performance. Such a negative effect of a dominance of condominium-type units on municipal waste generation was described by Ando and Gosselin (2005) or Lebersorger and Beigl (2011), in step with the suggestions of municipal officials. Nonetheless, the established insignificance is perhaps owing to the fact that environmental attitudes of people living in a condominium are not very different from those residing in family houses. People living in a condominium typically generate less waste than those occupying a family house, but typically also harbor a greater disposition to waste separation. The results suggest to a municipality that there is no virtual difference in servicing a condominium or a single-family house in terms of MSWM performance as differential benefits or disbenefits are nil. Of course, these differences must be understood on the scale of all housing units in the municipality. Municipal officials also reckoned that concentration of recreational dwellings should be negatively related to MSWM performance. Their views are confirmed by the analysis, and are consistent with the observations of Lebersorger and Beigl (2011). Since recreational dwellings are “secondary residences” populated by occasional visitors who are less troubled by responsibility in waste generation and Czech legislation offers no coercive mechanisms, municipalities are put into a stalemate position.
* Finally, population to built-up area (**z12**), as a measure of population density, was found of no statistical significance. Empirical literature offers mixed results on the effect of population density ranging from positive (Benito-López et al., 2011; Romano et al., 2020; Romano and Molinos-Senante, 2020) through inconsistent (Guerrini et al., 2017) to even negative (Worthington and Dollery, 2001; Llanquileo-Melgarejo et al., 2021). The reason for such an inconsistency might lie in the possible “break” observed from a certain size of municipality. For instance, Dubin and Navarro (1998) reported a positive effect only for municipality size up to 20,000 inhabitants. It is unlikely that threshold analysis would bring in any meaningful insights in this case as municipalities in the sample are by all standards small and dominated by municipalities of 1,000 inhabitants at most.

It should be noted here that there are, of course, a variety of other variables that could be insightful for MSWE performance. For instance, Lebersorger and Beigl (2011) provide a list of such factors. Unfortunately, the limited data availability for Czech municipalities prevents further explorations beyond those that have been conducted so far. Nevertheless, a commonly examined question of the presence of economies of scale can be addressed at this point. Examples of plentiful studies investigating this aspect include Carvalho et al. (2015), Carvalho and Marques (2014), Simões et al. (2013) or Bartolacci et al. (2019). A general conclusion of these studies that the optimal municipal size for MSWM is in the region of 20,000 – 30,000 people. A difficulty here is that the Czech Republic possesses a specific municipal structure consisting dominantly of very small municipalities ranging typically from several hundred to one thousand inhabitants (the median size for the whole country is actually below 1,000 inhabitants). In the sample, only six municipalities have more than 10,000 inhabitants amongst almost 500 municipalities, acting thus more like a few outliers than typical municipalities that would permit generalizations. The present results do not support any valid conclusion about the optimal size of a municipality. Even if such a calculation were available, practical implications from this information are very limited as there is very strong reluctance towards any kind of merger or division amongst Czech municipalities. One way to overcome these uncooperative stances might lie in promoting intermunicipal cooperation in this area, which seems to produce consistent positive, albeit somewhat small, benefits over time (Struk and Bakoš, 2021).

Another often debated issue in this type of studies is the question of the optimal choice between public and private provision of WM service. There seems to be a consensus that there is no clear evidence which type of provision results in more satisfactory MSWM performance. The evidence remains mixed (e.g., Bel and Warner, 2008; Bel et al., 2010), and even a recent study by Bel and Gradus (2018) considers this topic to be still open. The role of ownership in provision of WM service has already been examined for Czech municipalities (Struk, 2018) with basically the same conclusion of no clear preference.

**5. Conclusion**

This study presents a unique case study focused upon Czech municipalities that fulfill their functions in the sphere MSWM in a spatially fragmented environment with a preponderance of small municipalities. Irrespective of their size, Czech municipalities are mandated by law to secure WM service, and struggle to comply with this mandate with a tight municipal budget. The study identifies a set of 12 variables answering to the environmental context of MSWM and examines their effect upon municipal WM performance by using a data set on 470 municipalities in the South Moravian Region of the Czech Republic. Nine contextual variables depict the organizational conditions of WM service, and three are general urban factors barely under the control of municipalities. Some of these variables have not been yet used in the follow-up analysis, whilst others are used quite frequently. This study belongs amongst the first undertakings sui generis conducted for a post-Socialist country from Central and Eastern Europe.

Performance in MSWM was approached from the perspective of the municipality that is less interested in total waste generation, but its chief goal is securing WM service for all its citizens at a minimum cost represented by MSWE. To the municipality, lower generation of residual waste is more a practical concern motivated by the EU separation targets, and less a consequence of environmental awareness. These conflicting aspects are taken into consideration by postulating four different production models of WM. Models I and II both emphasized the goal to provide a specific service to the municipal population at a minimum of MSWE, but Model II added an environmental perspective focusing on waste separation relative to total waste generation. Model III only compared these environmentally favorable outcomes with MSWE, whilst Model IV was only ancillary as it reviewed the ability to handle waste separation relative to the service demanded.

The performance assessment and the subsequent analysis of the influence that the identified contextual variables exert employed DEA with full and order-*m* partial frontiers. In the manner of UTC analysis, unconditional scores were confronted with scores conditional on the environmental context and non-parametrically regressed upon the identified contextual factors. The factors with a positive effect include operating days of an HWRC per week, availability of drop-off sites (especially if one drop-off site serves 600 inhabitants at least), whereas negative effects were ascertained for waste separation and green waste collection programs, and concentration of recreational dwellings. The analysis issues Czech municipalities with interesting policy implications, which are hopefully transferable to other countries or regions with highly fragmented urban structures. For a Czech municipality, high waste collection frequency does not translate into better performance, and a similar neutral effect is also discovered for residual waste bin records in spite of some beneficial practical aspects. To improve on performance in MSWM, Czech municipalities are advised to open their HWRCs to the public as many days a week as conditions allow, and to maintain a network of drop-off sites with sufficient coverage (since a smaller density of drop-off sites may impair performance). It is sort of surprising that curbside collection of recyclables are found without effect upon performance, but this may be owing to the fact of the relative recency of this measure in the year 2012 for which the data are available. Additionally, waste separation incentives are found without beneficial effects upon performance in MSWM, and so are green waste collection programs. The finding is uncommon as these programs are normally quite effective when the main focus is upon increasing the waste separation rate.

Results as these can be useful for policy makers and waste practitioners when setting up a WM system or a general WM framework. Especially factors that are within the reach of the municipality or a governing body and that have a significant influence upon performance in MSWM are of interest and must be pinpointed. Their knowledge can be utilized to the benefit of municipalities, particularly in situations when there are numerous and small municipalities that are understaffed and unable to properly analyze the WM process and evaluate possible effect of potentially influential factors.

Although the four production models of WM service gave harmonious results, this need not always be so. In fact, the input-output specification behind Models I – IV in which some variables alternate between inputs and outputs is far from ideal, but it rests upon the standpoint taken in looking at WM service. A further investigation is needed to reconcile different angles from which WM service can be scrutinized. A practical solution might be to assemble WM service as a several-stage process, in which, e.g., MSWE is employed to match the potential demand (population size, built-up area, housing units) in Stage I, and then actual demand (generation of waste) is transformed into the actual demand (generation of waste) in Stage II. These considerations open a new direction of research in MSWM performance.

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**Appendix** **A**

Descriptive statistics of input-output data and contextual variables

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Mean | Standard deviation | Median | Minimum | Maximum |
| Production variables |  |  |  |  |  |
| MSWE | 659.898 | 1932.787 | 319.385 | 20.867 | 34798.929 |
| Population | 1083.100 | 2343.779 | 589.000 | 36.000 | 34073.000 |
| Built-up area | 16.932 | 21.687 | 11.700 | 1.500 | 281.800 |
| Housing units | 380.568 | 926.722 | 198.500 | 14.000 | 13813.000 |
| Generation of separated waste | 134.826 | 362.013 | 45.778 | 0.000 | 5178.544 |
| Generation of non-separated waste | 225.937 | 463.664 | 118.764 | 8.886 | 6179.644 |
| Generation of total waste | 360.763 | 810.420 | 167.055 | 13.385 | 11358.188 |
| Contextual variables |  |  |  |  |  |
| z1 (MSW collection frequency/month) | 2.167 | 0.565 | 2.000 | 0.250 | 4.000 |
| z2 (bin records) | 0.349 | 0.477 | 0.000 | 0.000 | 1.000 |
| z3 (HWRC open per week) | 0.595 | 1.257 | 0.000 | 0.000 | 6.000 |
| z4 (availability of free-of-charge HWRC) | 0.511 | 0.500 | 1.000 | 0.000 | 1.000 |
| z5 (separation drop-off sites) | 4.904 | 10.428 | 3.000 | 0.000 | 145.000 |
| z6 (population per separation drop-off site) | 233.859 | 170.270 | 195.267 | 0.000 | 1412.000 |
| z7 (curbside collection of recyclables) | 0.153 | 0.361 | 0.000 | 0.000 | 1.000 |
| z8 (waste separation incentive program) | 0.023 | 0.151 | 0.000 | 0.000 | 1.000 |
| z9 (green waste collection program) | 0.194 | 0.378 | 0.000 | 0.000 | 1.000 |
| z10 (share of condominium housing units) | 0.082 | 0.119 | 0.049 | 0.000 | 0.897 |
| z11 (share of recreational dwellings) | 0.102 | 0.154 | 0.053 | 0.000 | 2.154 |
| z12 (population to built-up area) | 53.577 | 21.172 | 51.408 | 8.929 | 202.788 |

Notes: Units of measurements are reported in Tables 1 and 2. Statistics are affected by the fact that a good many contextual variables (z2, z7, z8, z9) are “yes/no” variables, alternatively with a “partly” answer (z9).

**Appendix** **B**

Spearman correlations between unconditional and conditional scores and UTC ratios yielded by different input-output specifications under full frontiers

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type of scores | | Model I | | | Model II | | | Model III | | | Model IV | | |
| U score | C score | UTC ratio | U score | C score | UTC ratio | U score | C score | UTC ratio | U score | C score | UTC ratio |
| Model I | U score | 1.000 |  |  |  |  |  |  |  |  |  |  |  |
| C score | 0.389 | 1.000 |  |  |  |  |  |  |  |  |  |  |
| UTC ratio | -0.892(+1) | -0.058 | 1.000 |  |  |  |  |  |  |  |  |  |
| Model II | U score | 0.958 | 0.368 | -0.860(+1) | 1.000 |  |  |  |  |  |  |  |  |
| C score | 0.338 | 0.748(+1) | -0.025 | 0.352 | 1.000 |  |  |  |  |  |  |  |
| UTC ratio | -0.888(+1) | -0.120 | 0.956 | -0.925(+1) | -0.088 | 1.000 |  |  |  |  |  |  |
| Model III | U score | 0.217 | 0.064 | -0.219 | 0.361 | 0.099 | -0.347 | 1.000 |  |  |  |  |  |
| C score | 0.192 | 0.472 | 0.017 | 0.244 | 0.514 | -0.060 | 0.317 | 1.000 |  |  |  |  |
| UTC ratio | -0.091 | 0.298(–2) | 0.263(–2) | -0.209(+1) | 0.311(–2) | 0.350(–3) | -0.693(+5) | 0.324(–2) | 1.000 |  |  |  |
| Model IV | U score | 0.189 | 0.061 | -0.187(+1) | 0.333 | 0.081 | -0.317 | 0.974 | 0.308(–2) | -0.664(+4) | 1.000 |  |  |
| C score | 0.135 | 0.427 | 0.065 | 0.176 | 0.452 | -0.001 | 0.301(+1) | 0.804(+1) | 0.308 | 0.314 | 1.000 |  |
| UTC ratio | -0.094 | 0.267 | 0.249 | -0.213(+1) | 0.290(–2) | 0.341(–3) | -0.653(+4) | 0.298(–2) | 0.947 | -0.674(+4) | 0.353(–2) | 1.000 |

Notes: U score and C score represent unconditional and conditional score, respectively; whilst UTC ratio is the unconditional-to-conditional-score ratio. Superscripts combining +/– with a figure going from 1 to 5 highlight cases where Spearman correlation is greater (+) or lower (–) than Pearson correlation and the adjacent figure shows the magnitude of the absolute difference in the range from 0.100 to 0.199 at most (labelled by 1), from 0.200 to 0.299 at most (labelled by 2), etc., from 0.500 to 0.599 at most (labelled by 5).

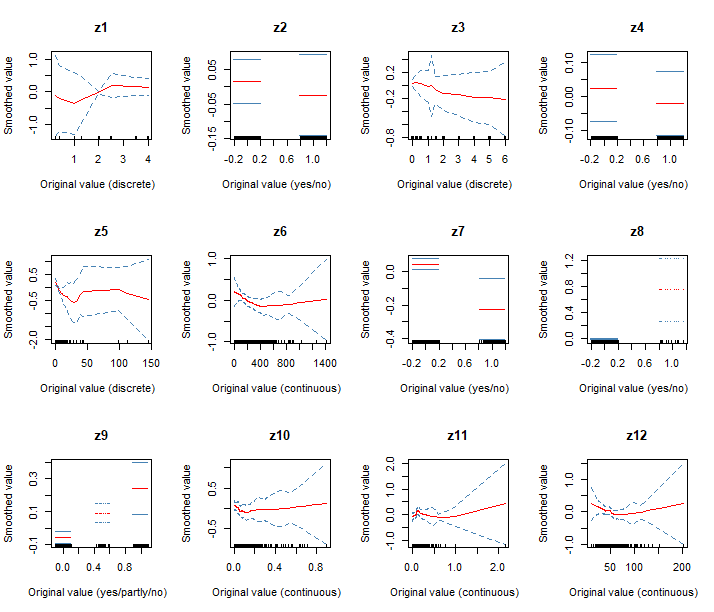
Spearman correlations between unconditional and conditional scores and UTC ratios yielded by different input-output specifications under partial frontiers (for *m* = 150)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type of scores | | Model I | | | Model II | | | Model III | | | Model IV | | |
| U score | C score | UTC ratio | U score | C score | UTC ratio | U score | C score | UTC ratio | U score | C score | UTC ratio |
| Model I | U score | 1.000 |  |  |  |  |  |  |  |  |  |  |  |
| C score | 0.996 | 1.000 |  |  |  |  |  |  |  |  |  |  |
| UTC ratio | 0.987 | 0.997 | 1.000 |  |  |  |  |  |  |  |  |  |
| Model II | U score | 0.982 | 0.995 | 0.999 | 1.000 |  |  |  |  |  |  |  |  |
| C score | 0.885 | 0.893 | 0.895 | 0.895 | 1.000 |  |  |  |  |  |  |  |
| UTC ratio | 0.879 | 0.893 | 0.900 | 0.902 | 0.984 | 1.000 |  |  |  |  |  |  |
| Model III | U score | -0.633(+1) | -0.623(+1) | -0.612(+1) | -0.605(+1) | -0.300 | -0.292 | 1.000 |  |  |  |  |  |
| C score | -0.583 | -0.579 | -0.573 | -0.569 | -0.261 | -0.250 | 0.983 | 1.000 |  |  |  |  |
| UTC ratio | -0.554 | -0.553 | -0.549 | -0.546 | -0.241 | -0.227 | 0.960 | 0.994 | 1.000 |  |  |  |
| Model IV | U score | 0.876 | 0.892 | 0.900 | 0.903 | 0.973 | 0.995 | -0.293 | -0.298 | -0.224 | 1.000 |  |  |
| C score | 0.873(–1) | 0.891 | 0.900 | 0.904 | 0.961(–1) | 0.988 | -0.249 | -0.252 | -0.225 | 0.995 | 1.000 |  |
| UTC ratio | -0.665(+2) | -0.649(+2) | -0.633(+2) | -0.624(+2) | -0.324(+1) | -0.324(+1) | 0.961 | 0.906 | 0.866 | -0.329 | -0.337 | 1.000 |

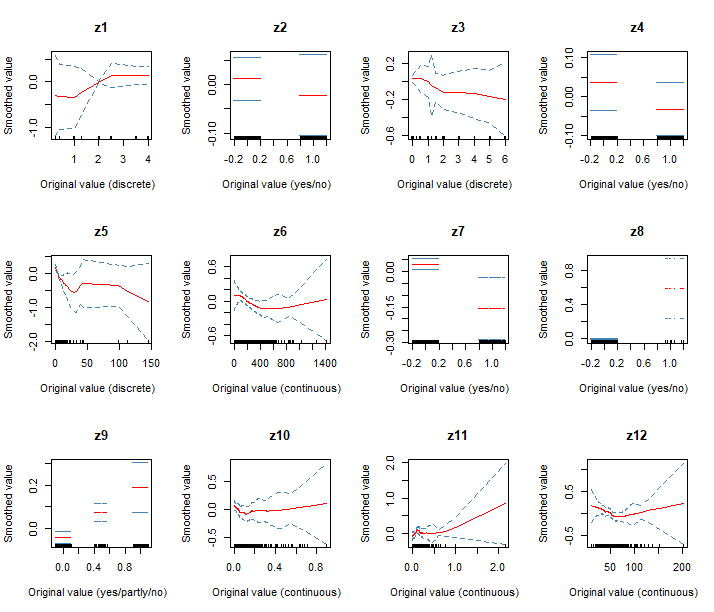
Notes: U score and C score represent unconditional and conditional score, respectively; whilst UTC ratio is the unconditional-to-conditional-score ratio. Superscripts combining +/– with a figure going from 1 to 2 highlight cases where Spearman correlation is greater (+) or lower (–) than Pearson correlation and the adjacent figure shows the magnitude of the absolute difference in the range from 0.100 to 0.199 at most (labelled by 1), from 0.200 to 0.299 at most (labelled by 2).

**Appendix** **C**

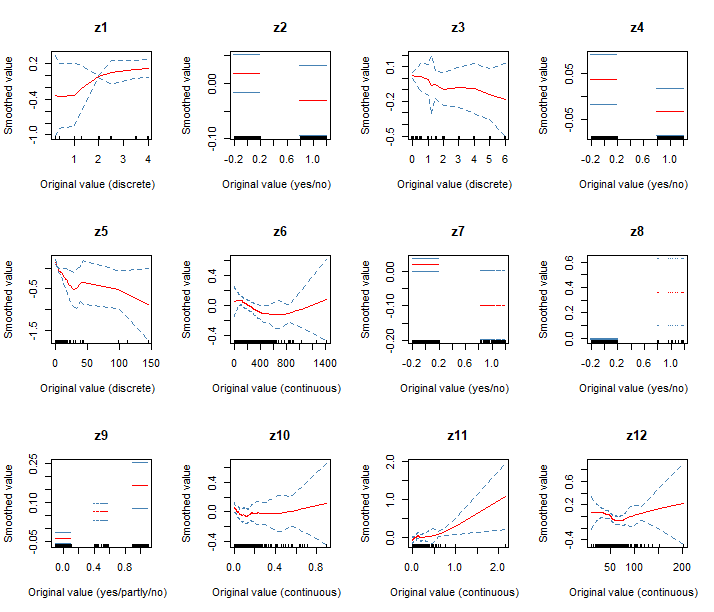
Marginal effects of contextual variables upon MSWM performance in Model I under partial frontiers (for *m* = 150)



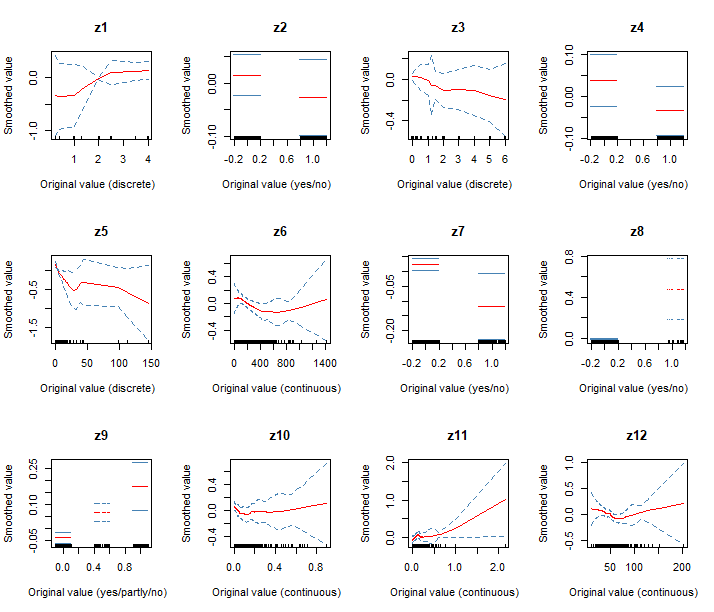
Marginal effects of contextual variables upon MSWM performance in Model II under partial frontiers (for *m* = 150)



Marginal effects of contextual variables upon MSWM performance in Model III under partial frontiers (for *m* = 150)



Marginal effects of contextual variables upon MSWM performance in Model IV under partial frontiers (for *m* = 150)



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1. A housing unit is understood here as a self-contained and separate place of abode intended for habitation by one person or more people who maintain a common household. One house can agree with one housing unit (e.g., a single-family house) or can encompass several housing units (e.g., a condominium). [↑](#footnote-ref-1)
2. Surely, this is not to say that residual waste should, or rather, could be eliminated. In fact, certain levels of residual waste are practically unavoidable, plus there are likely too many factors that influence this level in municipalities. Using residual waste as an undesirable output requires too strong an assumption regarding comparability in the environment of individual municipalities. [↑](#footnote-ref-2)
3. The attribute “difference” relates to the fact that non-separated (residual) waste arises residually as the difference between total waste and separated waste. In Model II placing total and separated waste generation on the output side implies implicitly minimization of residual waste generation, and in Models III and IV maximization of separated waste generation as an output conditional on total waste generation as an input is of an identical effect. [↑](#footnote-ref-3)
4. An HWRC is a designated facility with qualified staff where people can leave their separately collected waste in addition to drop-off sites or curbside collection, typically with a wider range of accepted waste fractions. An HWRC is operated commonly either by the municipality or a WM company. [↑](#footnote-ref-4)
5. This variable also includes a free-of-charge HWRC available in a neighboring municipality if there is such an agreement between the municipalities, not only the municipality in question itself. [↑](#footnote-ref-5)
6. A comprehensive treatment for multivariate with mixed data is provided by Li and Racine (2003, 2008) who construct a generalized product kernel consisting of marginal kernels specified individually for different categories of data and estimate bandwidths by cross-validation of the integrated squared error. Aitchison-Aitken kernels are used as marginals for categorical variables (including the “yes/no” type) and for discrete numeric variables, for numeric data there is a preference for the second-order Epanechnikov kernel (De Witte and Kortelainen, 2013; Cordero et al., 2015). The Gaussian kernel is unsuitable due to unbounded support. [↑](#footnote-ref-6)
7. The order *m* is an additional judgmental input with a history of its own. Whereas Cazals et al. (2002, p. 7) accentuate an economic point of view and interpretation, Daraio and Simar (2007, p. 114) try several values of *m* as a sensitivity exercise and choose a suitable small value for which the results stabilize. A more robust and perhaps presently agreed-upon avenue is the approach of Simar (2003) who proposed computing unconditional partial frontier efficiency measures for a grid of values of *m* and then choose the threshold at which the decline in the percentage of super-efficient firms levels off. The procedure is comparable to that for constructing a scree plot in principal component analysis or an elbow plot in cluster analysis. [↑](#footnote-ref-7)
8. Formally, if the unconditional production possibility set is  and the production possibility set conditioned on a value  is , then separability entails  for all possible values of . [↑](#footnote-ref-8)
9. Hazardous waste and other remaining waste categories generated in municipalities were excluded as they were not regularly collected by all municipalities or in all HWRCs in the reference year 2012. In no manner is this harmful or distortive to the analysis as these waste categories did attribute only for a very small fraction of total municipal waste. [↑](#footnote-ref-9)
10. For instance, Daraio et al. (2020) identified for a sample of 303 banks the same reasonable value . [↑](#footnote-ref-10)