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CIRCULAR ECONOMY EFFICIENCY IN THE CONTEXT OF WASTE MANAGEMENT IN THE SELECTED CENTRAL AND EASTERN EUROPEAN COUNTRIES – EVIDENCE FROM DEA AND FRACTIONAL REGRESSION ANALYSIS

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ABSTRACT. Sustainability and optimizing waste management efficiency through circular economy principles have become significant trends in recent research. This study aims to compare the circular economy efficiency within the waste management framework in selected Central and East European countries. To achieve this, the research employs Data Envelopment Analysis (DEA) and Fractional Regression Analysis, specifically using the Slack-Based Measurement model. This model measures efficiency by referencing the inefficient Decision-Making Units (DMUs) rather than the origin of the coordinate system. Key variables such as GDP per capita, GDP growth rate, and circular economy indicators were selected and analyzed using Eurostat data from 2010 to 2022. The findings reveal varying potentials for improving the efficiency of hazardous and non-hazardous waste management in the countries investigated. Additionally, differences in the mutual influence of selected variable indicators on waste efficiency are identified using Fractional Regression Analysis. These insights emphasize the pivotal role of waste management in advancing circular economy policies.

JEL Classification: G39, L69, O14, Q59

Keywords: circular economy, waste management, Data Envelopment Analysis, efficiency score, Fractional Regression Analysis

Introduction

For many years, we have been part of a consumer society whose philosophy is based on the so-called linear model of the economy, governed by the "extract-produce-consume-dispose" cycle. This model is unsustainable because it relies excessively of cheap, readily available materials and energy. The consumption of limited resources and the increasing amount of waste produced with no possibility of reuse is a further blow to the environment, the planet and, most importantly, future generations. An alternative is represented by the circular economy (CE) model. This model focuses on material efficiency, limiting the waste of resources and reusing waste in the life cycle of new products.

Korhonen *et al.* (2018) presented a definition of circular economy based on the three pillars of sustainability: environmental, economic and social. Geissdoerfer *et al.* (2017) defined sustainability as the *"Balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations"*. Many other authors agree that sustainability can help businesses implement the principles of CE (Bilan *et al.*, 2017; Kravchenko *et al.*, 2019; Mishchuk *et al.*, 2023; Niero *et al.*, 2017; Sehmen *et al.*, 2019; Streimikiene *et al.*, 2024).

Circular economy, in the context of sustainability, brings several significant benefits. It concerns the sustainable use of resources in the fight against climate change and environmental protection. It is also anticipated that CE it will enhance the level of innovation and create new employment opportunities. The application of circular economy is anticipated to not only minimize and enhance waste management, but also to increase recycling and conserve natural resources (Zhidebekkyzy *et al., 2023*). According to the Ellen MacArthur Foundation (2022), this economic model is based on renewal and regeneration. In order to achieve sustainable growth and minimize negative environmental impacts, numerous national and international entities are currently implementing policy strategies and programs aimed at promoting a circular economy. CE indicators are essential tools for measuring progress towards the goals of this concept. The efficiency of the circular economy is often linked to the level of waste management. This study aims to use Data Envelopment Analysis and Fractional Regression Analysis to compare the current state of circular economy efficiency in the context of waste management in selected countries of the European Union and to point out the main priorities supporting the implementation of the CE model. A research gap was identified precisely in searching for dependencies between waste management efficiency scores and selected indicators of the circular economy or macroeconomic indicators in the broader context of European countries and their subsequent presentation.

1. Literature review

The concept of the circular economy has developed for many decades and has its historical background. The foundations of this idea date back to the 19th century. The foundations of the later modern concept of the circular economy was laid by some economic pioneers such as David Ricardo, John Stuart Mill, Thomas Malthus, Walter Stahel, and others. Over the last decade, scholars and practitioners have increasingly embraced the concept of CE. A significant influence on the development of CE was the concept of 3R (Reduce-Reuse-

Recycle), which has been published, analysed and developed since the 70s of the 20th century. The concept of 3R has been focused on reducing consumption and waste production, followed by supporting the reuse of products and materials where possible or recycling, which involves collecting and processing materials from waste so that they can be used again in the production of new products. In their study, Dong *et al.* (2021) explain the importance of all three aspects and state that the concept of 3R thus presents the fundamental principles of CE. Another important concept that played a role in shaping CE was Eco-design at the end of the 20th century. It is the design of products and services with regard to environmental impacts. Regarding this issue, significant representatives include Braungart and McDonough (2010), the co-authors of the book *"Cradle to Cradle: Remaking the Way We Make Things"*. This book introduces the concept of *"Cradle to Cradle"*, which emphasizes the design of products so that they are fully renewable and recyclable, which is an essential aspect of eco-design. Their work focuses on transforming the way we make and use things so that they are environmentally friendly and reusable. Currently, the 21st century is marked by significant efforts to transition to a circular economy. Today, it is a preferred topic, supported by many international organizations, national governments, and specific companies. The reason is the still insufficient of waste management efficiency and its negative environmental impact. The Ellen MacArthur Foundation has become a significant player in the CE. The Foundation's report *"Towards the Circular Economy"* (2013) contains essential principles related to this economic model. Although many efforts have been made to define the essence of a CE, it is not possible to choose the 'best' one, as the whole concept is complex and dynamic, and can be interpreted in different ways depending on the context and goals. The analysis conducted by Kirchherr *et al.* (2023) on 221 recent definitions of CE revealed noteworthy observations. Firstly, over the last five years, the concept has experienced both consolidation and differentiation. Secondly, there are emerging trends in definitions that may rather have higher significance for academic discourse than practical implementation. Thirdly, scholars are increasingly advocate for a fundamental systemic shift to facilitate CE, especially within supply chains. Fourthly, while sustainable development is often regarded as the primary goal of CE, questions persist regarding its potential to promote environmental sustainability and economic development simultaneously. Individual definitions of CE may be relevant for different purposes and perspectives. Even so, it is possible to highlight the following definition from the Ellen MacArthur Foundation (2022), which states that circular economy is an economy based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

The application of the circular economy can be applied in many industrial sectors. The results of applying CE principles in the food industry are self-evident. The authors Albizzati, Tonini, and Astrup (2021) have been addressing the issue of environmental sustainability of the food system in the context of CE for an extended period. Another example is Tingley, specializing in food systems and sustainability, whose work also encompasses circular solutions (Sinkko *et al.*, 2023). Another attractive segment is the textile industry. Some authors discuss the issue of low textile recycling rates and the connection between clothing design and textile recycling (Karell and Niinimäki, 2019). The study of Hornbuckle *et al.* (2023) is also noteworthy, where the authors discuss the current state and future potential of the most prevalent synthetic fibre, polyester, as a circular textile. The construction industry sector in connection with CE is also a frequently discussed topic (Zink and Geyer, 2017). The wood processing industry has enormous potential for utilizing recycled materials as a repeated input resource. Examples include the results of studies, such as those by Ginevičius (2022), Jarre *et al.* (2020), Sherwood (2020), Osvaldová *et al.* (2023), Susanty *et al.* (2020) and Zielińska *et al.* (2023).There is also high potential for CE in the agricultural sector. Matysik-Pejas *et al.* (2023) presented a study focused on identifying and evaluating the spatial diversification of agricultural production, economic conditions, and their connection with the circular economy across EU countries. However, CE also has its justification in the services sector, such as transportation and logistics, which are the focus of attention of Beames *et al.* (2021). A critical view of the current economic model and possible alternatives in some areas of industry is also presented in a study by Raworth (2017). Valuable crosscountries comparisons are available in study of Naomi & Akbar (2021) and Štreimikienė (2023). *Table 1* summarizes some of the studies that deal with the DEA of EU countries their efficiency in implementing the circular economy.

Table 1. Comparative table of studies dedicated to CE efficiency in the EU

Authors	Scope	Methodology	Inputs	Outputs
Giannakitsidou *et al.* (2020)	Ranking European countries based on their environmental and circular economy performance.	DEA with common weights	Municipal Solid Waste (MSW) generated; Basic human needs; Foundations of wellbeing opportunity	Recycling rate of MSW; Circular material use rate
Halkos and Aslanidis (2023)	New circular economy perspectives on measuring sustainable waste management productivity	DEA together with Malmquist Productivity Index	Energy use; Labour force; Gross fixed capital formation	GDP; Waste generation
Robaina *et al.* (2020)	Circular economy in plastic waste - Efficiency analysis of European countries	Multidirectional Efficiency Analysis (MEA)	Capital invested; Labour; Energy consumed	GDP; CO2 emissions; Plastic waste and recycling; Plastic recovery
Marques and Teixeira (2022)	Assessment of municipal waste in a circular economy countries share identical performance?	DEA; Fractional regression	Municipal Waste generated; Innovation in WM-related technologies; Domestic Material Consumption; Gross Domestic Product	Recycling Rate of Municipal Waste; Circular Material Use Rate
Horvat *et al.* (2023)	Assessing circular economy performance of European countries and Serbia using Data Envelopment Analysis	DEA; Tobit regression	Generation of municipal waste	Recycling rate of municipal waste; Share of energy from renewable resources

Source: *own compilation*

In the current study, the Data Envelopment Analysis (DEA) methodology is utilized. DEA estimates the efficiency scores among different units referred to as Decision Making Units (DMU). It was developed by Charnes, Cooper and Rhodes (1978) with the so-called CCR model, which does not consider the influence of different scales of DMUs. According to Charnes *et al.* (1985), the efficiency of DMUs can be obtained from the maximum ratio of weighted outputs to weighted inputs. Banker, Charnes and Cooper (1984) further developed the DEA BCC model that is applicable in so-called variable returns to scale and assess the pure technical efficiency of the DMUs. In the literature, the authors implement a variety of inputs and outputs to estimate the efficiency of CE and waste management. As they are strongly interconnected, some researchers include waste management as inputs for CE efficiency, while others use due to policy decisions in outputs. The table shows that authors implement DEA in different types and combinations. Some publications include regression analysis as a second stage of DEA. Recycling, either as a rate or quantity, is a common output in these papers. There is also a variety of implementations of some variables in DEA and regression analysis. Some authors like Horvat *et al.* (2023), used GDP per capita as a regression variable, while others, such as Halkos and Aslanidis (2023) or Robaina *et al.* (2020), used it as a DEA output.

An essential aspect of advancing CE is the publication and comparison of possible CE indicators. Such indicators have their origin in the attempt to quantify and monitor the success of the implementation of circular policies and practices in achieving the set goals. They are also important for focusing on specific results and informing the public, as efforts are made to raise awareness of the issue. Circular economy indicators are developed and managed by government institutions, international organizations, and non-profit organizations that deal with sustainability and environmental assessment. It is possible to include Eurostat - the statistical office of the European Union, the Ellen MacArthur Foundation, and environmental agencies such as the Environment Agency and Environment Protection Agency. Several authors have dealt with the analysis and comparison of CE indicators. For example, in a study by Smol (2023), national strategies (roadmaps) for implementing CE in selected European Union countries were identified. In addition to this, this paper also presents an inventory of performance indicators, which have been indicated in the selected CE national strategies. The article of Mazur-Wierzbicka (2019) was focused on a multidimensional comparative analysis of the implementation of the circular economy in EU countries. The study that reviews existing and relevant published studies on the circular economy in developed countries, including Australia, is interesting as well, since it discusses the implications for Korea (Halog and Anieke, 2021). A study by Vranjanac *et al.* (2023) compares the development of circular economy indicators in the EU-28 countries with using of the Eurostat database. Zhidebekkyzy *et al.* (2022) analyzed the potential of waste management system as part of the circular economy using synthetic control method. The Eurostat database is the information database for the needs of this study. Eurostat provides the EU with statistics at a European level, which are used to compare countries in many macroeconomic indicators as well as CE indicators. For the purposes of DEA and for Fractional Regression Analysis, the variables specified in the methodology section were used.

The aim of the study is to utilize Data Envelopment Analysis and Fractional Regression Analysis to compare the current state of circular economy efficiency in the context of waste management among selected countries of the European Union (Czech Republic, Slovak Republic, Poland, Hungary and Bulgaria) and to identify the main priorities supporting the implementation of the circular economy model. On the one hand, the results will fill a research gap in the field, and on the other hand, they will provide a foundational database for further research and a better understanding of the level and dynamics of circular economy implementation in European countries, which may also provide support for a model of sustainable resource management in the region. Based on the literature review and analyses of the previous research, the subsequent research questions (RQ) were formulated:

RQ1: Is it possible to identify the different potential for improving hazardous and non-hazardous waste efficiency management in the investigated countries by applying the DEA model?

RQ2: Are there differences in the mutual influence of GDP per capita, GDP growth rate, and selected circular economy indicators on waste efficiency in the analyzed countries?

2. Methodological approach

The research, focused on the analysis and comparison of circular economy efficiency in the context of waste management within selected European countries, was divided into three separate steps. The detailed specification of the methodological procedure for applying these steps is as follows:

Step I – in the first step of the research, a suitable information database for data acquisition, a time frame, and also selected input and output of waste management and CE indicators were identified. The advantage of these variables is their suitability for comparisons, as well as their potential for prediction in modelling. For the analysis and comparison of variables in selected European countries, the values on the Eurostat database (ec.europa.eu/Eurostat) for the period 2010-2022 were used and compared with the EU-27 average. The monitored variables were specified in step III of this study.

Step II - In the second step of the research, a comparative analysis of the identified variables of waste management and CE indicators was carried out in selected EU countries (Czech Republic, Slovakia, Poland, Hungary, and Bulgaria) using Data Envelopment Analysis and in the second step with using of Fractional Regression Analysis principles.

Step III - presentation of the results of the DEA model with estimation of all DMUs efficiency scores, which provides recommendations for reducing the quantities in waste treatment practices. Identification of significant influences of various factors (GDP per capita - GDPC, GDP growth rate - GDPR, Persons employed in CE sectors - EMPL, number of annually issued patents related to the CE - PATENT, investments in the CE – INV) on waste management efficiency.

Coelli *et al.* (2005) described the DEA model as a linear programming technique that creates a linear frontier which *"envelopes"* the observed DMUs. The DEA approach includes various models, from the classic ones to models like Slack Based Measurement (Tone *et al.*, 2020). DEA estimates the efficiency scores of all DMUs by comparing the efficiency of each unit with that of the best-performing DMUs. In radial models, efficiency is measured as the weighted ratio of the distances between the inefficient DMU and the frontier (Zhu, 2014). In the current study, is implemented the non-oriented Slack Based Measurement (Tone, 2002):

$$\min \rightarrow \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s}\sum_{r=1}^{s}\frac{s_r^+}{y_{r0}}} \tag{1}$$

subject to:

$$\sum_{j=1}^{n} \lambda_j x_{ij} = x_0 + s_i^- \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} = y_0 - s_r^+ \tag{3}$$

$$\lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0$$

Where: λ_j are the individual scalars of each DMU_j $j\epsilon[1, n]$, x_{ij} are the amounts of inputs of type i in DMU j, x_{i0} is the amount of i-th input of DMU_0 being under assessment. The y_{rj} are the outputs of type r in DMU j, and the consequent y_{r0} for the DMU, which is being assessed. The m and s are the number of inputs and the number of outputs consequently. The vectors s^+ and s^- are slacks of outputs and inputs. They present shortfalls in the outputs and excesses in the inputs. The DMU_o is SBM-efficient if $\rho=1$. The s^- expresses the input excess and s^+ presents the output shortfall.

In the current study the following DEA variables were defined:

- Inputs: waste disposal – landfill and other waste incineration. The DEA model (1) gives recommends for reducing the quantities of these waste treatment practices in inefficient DMUs.
- Outputs: waste recycling – a method of utilization that adds more value to the economy and implements the CE. Waste for energy recovery - this utilization alternative adds value through energy production.

Fractional Regression Analysis. The current study uses a fractional regression model (FRM) developed by Papke and Wooldridge (1996). According to Ramalho *et al.* (2011), the FRM only requires specification of the regression equation and type of the probability distribution, i.e., functional form. Papke and Wooldridge also confirmed that their model did not need any preliminary transformations. All described features of FRM make it very easily applicable and interpretable. The FRM is widely implemented with logit, probit, and the heteroskedastic probit functions. The estimation procedure is based on the Bernoulli log-likelihood function:

$$lnL = y_i ln\{G(x_i b)\} + (1 - y_i)\{ln[1 - G(x_i b)]\} \quad (4)$$

Where: yi is the dependent variable. The G(xib) is a known nonlinear function [59], 0< G(xib) <1. The vector b represents the coefficients of the covariates, where xi denotes explanatory variables.

The functional forms for the G(xib) used in the current research are:

$$\text{Logit: } G(xib)=\exp(xib)/\{1+\exp(xib)\} \quad (5)$$

$$\text{Probit: } G(xib)= \Phi(xib) \quad (6)$$

Where Φ is the cumulative function of the normal distribution.

The Fractional Regression Analysis is conducted in three steps. The first step involves preliminary correlation analysis to reveal relationship between variables and eliminate collinear variables from subsequent regression. The second step is backward elimination of the insignificant variables. The third one is providing a separate regression for collinear variables in order to induce empirically beneficial concussions and recommendations. The exogenous variables included in the regression equations are regressed against SBM scores foe hazardous and non-hazardous waste efficiencies. Post estimation involves regressing the SBM scores against the predicted values obtained from the equation and the squared predicted values ("sqfitted" - variable) or conducting the linktest (Heins *et al.*, 2020). If the sqfitted variable is significant, it indicates model misspecification, and the variables should be removed or modified. For FRM, the following variables were used: GDPC, GDPR, EMPL, PATENT and INV.

Regression analysis is conducted for each studied country over the research period and cross-sectional data are used for countries participating in DEA analysis. The following arguments were used to select the given countries. Regional interconnection of countries within Central and Eastern Europe with interconnected economies. Similarity of industrial structures and important orientation towards agriculture. Similarity of historical background, which affects their socio-economic development, and the availability of data necessary for analysis and comparison. The current study focused on how waste was utilized in the investigated countries. The waste generation is considered as a given condition under which the analysis was conducted. The DMUs in the DEA model (1) are 22 European Countries. This ensures that the 'rule of thumb,' which suggests that states the sum of inputs and outputs should be at least three times less than the number of DMUs is not violated. Countries were selected based on the available data in the Eurostat database for waste utilization, with a condition for maximum data availability (Eurostat, 2023a, b, c, d). The period of analysis spans from 2010 to 2022 reflecting the latest available data in Eurostat up to the conceptual creation date of this study.

3. Empirical results and discussion

It is important to note at the outset that in the literature review part there is a mention of several studies using the principles of DEA and FRM for waste management, but in most cases at the global or national level. It is for this reason that the authors are interested in comparing the current state of CE efficiency in selected Central and East European countries. Descriptive statistics results for the research period of 2010-2022 are presented in *Table 2*. The table presents statistics only for five investigated countries that are geographically close, industrially interconnected, and share similar socio-economic challenges.

Table 2. Descriptive statistics of the investigated countries in 1000 t.

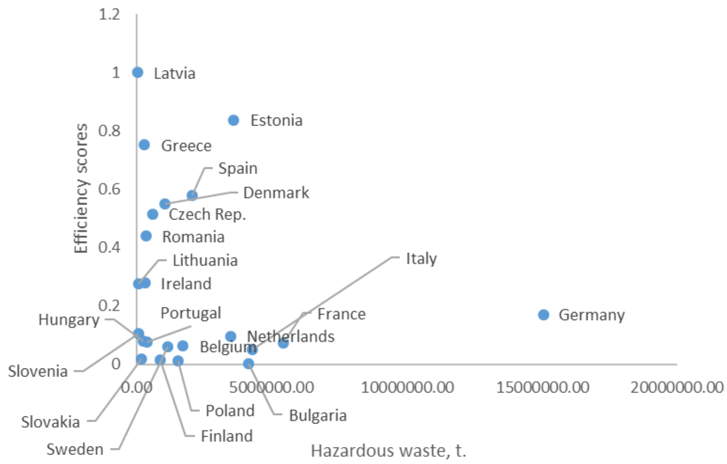
Hazardous waste										
	Disposal		Incineration		Energy recovery		Recycling		Generation of waste	
	AVE	VAR	AVE	VAR	AVE	VAR	AVE	VAR	AVE	VAR
Bulgaria	13089	4%	20	172%	5	173%	162	62%	13313	4%
Czechia	80	83%	73	16%	43	25%	476	31%	1424	17%
Hungary	97	28%	76	5%	27	24%	178	15%	569	13%
Poland	257	24%	157	12%	4	36%	1263	21%	2148	36%
Slovakia	107	32%	18	67%	5	26%	49	27%	423	10%
Non-hazardous waste										
	Disposal		Incineration		Energy recovery		Recycling		Generation of waste	
	AVE	VAR	AVE	VAR	AVE	VAR	AVE	VAR	AVE	VAR
Bulgaria	122302	23%	5	75%	372	57%	4050	57%	132516	19%
Czechia	3687	6%	6	18%	1017	19%	14628	60%	27249	24%
Hungary	5355	23%	9	30%	1052	14%	8469	42%	16290	5%
Poland	39894	12%	319	47%	4513	19%	111876	9%	169175	5%
Slovakia	3547	9%	29	51%	427	36%	3924	34%	9986	17%

Source: *Eurostat (2023a).*

The results presented in *Table 2* show that all the analysed countries have a higher variability in recycling both hazardous and non-hazardous waste compared to the variability of all EU countries. The table also presents the variability of the investigated countries through the coefficient of variation (VAR). However, when the variability values of the studied periods are too large, it means that recycling level or energy recovery level are not stable. This means that the ratio of outputs to inputs of waste management is not so stable and satisfactory. Bulgaria prefers landfill disposal as the primary waste utilization, while other countries achieve a better level of recycling. The highest levels are in the Czech Republic and Poland. Incineration is the least used utilisation in both types of waste. The Czech Republic has the highest variation in the generation of non-hazardous waste, while Poland has the highest variation in the generation of hazardous waste. However, Slovakia shows relatively low amounts of hazardous waste recycling.

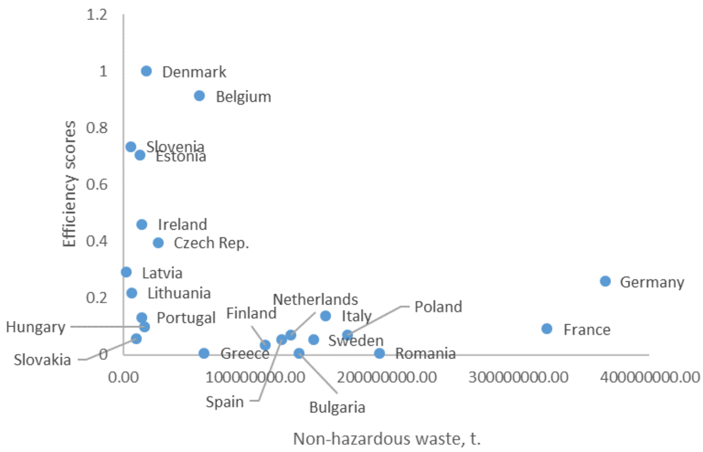
Subsequently, it is possible to proceed with the application of the DEA methodology and the subsequent quantification of efficiency scores (SBM scores) from DEA model (1) related to the generation of hazardous and non-hazardous waste. In the current study, the results from DEA-SBM are visualized to facilitate interpretation, utilizing the presentation of *Graphs 1, 2,* and *3*.

Averaged SBM scores for analysed countries according to hazardous waste generation are presented in *Graph 1*. The scores presented in the figure are averaged for the research period. Numerical quantification about hazardous waste efficiency management is as follows: Czech Republic (ρ=0.51), Slovakia (ρ=0.02), Poland (ρ=0.01), Hungary (ρ=0.08) and Bulgaria (ρ=0.002). The higher the score, closer to 1, the more ideal the condition. It is possible to state that only Czech Republic is much better than the others. It is even better than most of the EU countries from the group. Slovakia, Poland and Bulgaria are close to the bottom line, but the difference is that Slovakia generates less hazardous waste. Hungary performs slightly better, with efficiency levels close to those of Slovenia and Portugal. Its hazardous waste management is better than in Finland or Sweden, despite the latter being countries with a more developed circular economy. The results partially overlap with those derived by Callao et al. (2019). Latvia appears efficient in the current study and theirs. However, there are significant differences regarding countries like Sweden. Bulgaria and Slovakia are also not efficient in Callao's research. The key difference is that they used an input-oriented classical model and included GDP in the model's outputs. In the current research, the analysis is free from the influence of GDP in the DEA model.



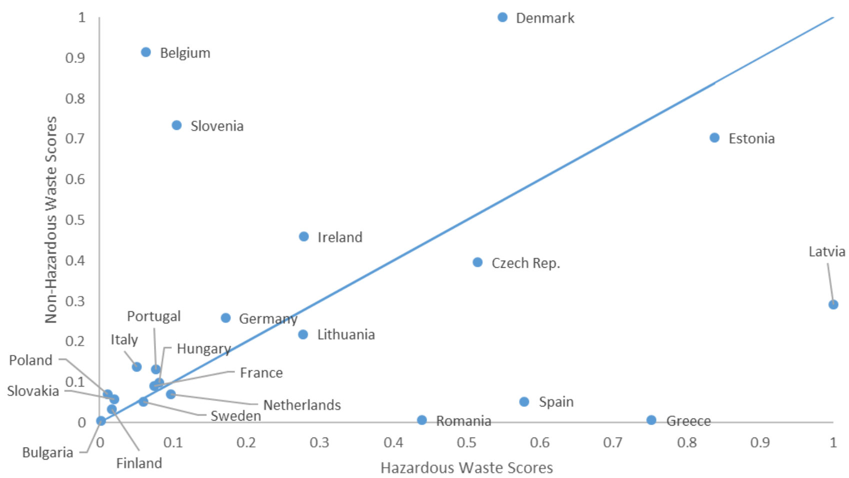
Graph 1. SBM efficiency according to average hazardous waste generation per year
Source: *authors' results*

SBM scores for selected analysed countries according to non-hazardous waste generation are presented in *Graph 2*. The numerical quantification of non-hazardous waste efficiency management is as follows: Czech Republic (ρ=0.39), Slovakia (ρ=0.06), Poland (ρ=0.07), Hungary (ρ=0.1) and Bulgaria (ρ=0.05). As previously mentioned, the closer the score is to 1, the closer to the ideal condition. The efficiency scores are higher than scores in hazardous waste management except those for marginal. This result reveals that the focus in that country was placed on hazardous waste. In other countries, the priority during the time of research was the management of non-hazardous waste. On average, for the 23 countries in the DEA, the efficiency scores are 0.27 for hazardous waste and 0.26 for non-hazardous waste. It can be assumed that these efficiency scores result from individual decisions made by each country, rather than being the outcome of an overall EU policy. This conclusion is supported by studies like Wilts *et al.* (2016). They analyzed the implementation of EU waste management policies in different EU countries. The results revealed a very high heterogeneity of policy implementation in the researched countries. An interesting fact emerged: countries like Estonia had local implementation of the EU policies, while the Netherlands did not. In the current research, Estonia surpasses the Netherlands in waste efficiency. The study presents a significant result by revealing the high efficiency of countries that were previously considered to have a big gap in the implementation of the EU circular economy legislation (Halkos and Petrou, 2016). This efficiency revelation is attributed to the nature of the DEA methodology, which uncovers hidden potential or constraints in each Decision-Making Unit (DMU).



Graph 2. SBM efficiency according to non-hazardous waste generation per year
Source: *authors' results*

Graph 3 shows the comparative efficiency of hazardous and non-hazardous waste for the countries under study. The solid line represents the linear variation with respect to the abscissa. The results indicate that out of 22 countries, 10 focused more on non-hazardous waste management than on hazardous. There is a main group of countries with small differences between the two efficiency scores, revealing that waste management in those countries was not strategically oriented towards one type of waste. The only exception to this pattern is the Czech Republic which is evidently among the best performers among all the countries studied.



Graph 3. Comparison between SBM efficiencies for two types of waste
Source: *authors' results*

Several authors dealt with the issue of quantifying the efficiency of waste management with emphasis on circular economy in their work. The findings align with those of the current study. In the Central European region, Hadad *et al.* (2023) present intriguing discoveries regarding the optimising of waste resource utilization efficiency using a CE framework. Their conclusions focus on waste treatment practices in Poland with emphases on potential energy utilization methods like biogas production or incineration. Moustakas and Loizidou (2023) and Kuźmiński et al. (2023) examined various waste management approaches and proposed ways to enhance efficiency (particularly in landfilling and recycling). The European Environmental Agency's report on Municipal waste management across European countries (2017) summarized the efficiency of municipal waste management in 32 European countries. The SBM model (1), using DEA principles, provides very useful information with projected values of inputs and outputs. The deficiencies estimated by this model indicate the variations in quantities that each country should decrease or increase to achieve higher efficiency in waste management. *Table 3* presents the actual and optimal weights of waste utilization alternatives.

In the context of the research question RQ1, the results from the DEA model can help identify different potentials for improving the efficiency of hazardous and non-hazardous waste management in the investigated countries. For example, *Table 3* indicates that Bulgaria has significant room for improvement in waste management. The country needs to increase recycling of hazardous waste by 51% and reduce disposal by 80%. Similarly, there is a need to increase recycling of non-hazardous waste by 76% and significantly reduce disposal by 85%. This model (1) is capable of generating similar conclusions and recommendations for each of the analyzed countries. Poland has very good results for recycling and operates at an almost optimal level. Slovakia needs a significant reduction in disposal (50% for hazardous and 37% for non-hazardous waste). The Czech Republic is also almost optimal for non-hazardous waste, although it requires an 11% reduction in disposal and needs some actions for hazardous waste (improvement of energy use by 8%). Hungary falls between Bulgaria and Poland but has a better structure. It requires significant attention to disposal. It is also interesting to note that waste incineration is not recommended or is minimized in every country.

Table 3. Optimal Waste Utilization Structure Provided by the SBM DEA Model

Hazardous waste (H)	Disposal		Insineration		Energy recovery		Recycling	
	Actual	Optimal	Actual	Optimal	Actual	Optimal	Actual	Optimal
Bulgaria	99%	19%	0%	0%	0%	30%	1%	52%
Czechia	12%	3%	13%	2%	7%	11%	67%	84%
Hungary	26%	4%	20%	1%	7%	11%	46%	84%
Poland	15%	4%	9%	2%	0%	16%	76%	78%
Slovakia	60%	10%	9%	0%	3%	21%	28%	70%
Non-Hazardous waste (N-H)	Disposal		Insineration		Energy recovery		Recycling	
	Actual	Optimal	Actual	Optimal	Actual	Optimal	Actual	Optimal
Bulgaria	97%	12%	0%	0%	0%	9%	3%	79%
Czechia	20%	9%	0%	0%	6%	12%	74%	79%
Hungary	36%	9%	0%	0%	7%	14%	56%	77%
Poland	26%	12%	0%	0%	3%	21%	71%	67%
Slovakia	46%	9%	0%	0%	5%	15%	48%	76%

Source: *authors' calculations*

Several authors have addressed a similar issue of utilizing DEA for waste management assessment in their studies. There is often a problem in defining the production boundary of DEA. Although the DEA frontier may be correctly perceived as a production frontier, it must be remembered that DEA is ultimately a method for performance evaluation and benchmarking against best practice (Cook *et al.*, 2014). In the study by Murray Svidroňová and Mikušová Meričková (2022), the authors emphasize the importance of separate waste collection in increasing the efficiency of municipal solid waste collection and disposal using DEA principles. The main conclusion of their research is that outsourcing the collection and disposal of solid waste in Slovak municipalities is the dominant method of service provision. The study by authors Taboada *et al.* (2020) addressed the evaluation of waste management efficiency, particularly concerning hazardous waste in European countries, using Data Envelopment Analysis. The main outcome of the paper was the proposed methodology for evaluating the performance of waste policy. Its adaptive nature promotes continuous improvement and overcomes limitations posed by poor quality metrics, data and parametric indicators. Another intriguing study was conducted by Gökgöz and Yalçın (2023), who explored effective waste management and its connection to the circular economy in the EU region using DEA and the slack-based measure (SBM) methodology. The empirical research delves into the factors influencing the volume of waste generated in the EU region. Among these factors, population density, GDP per capita, and tourism were identified. The application of Fractional Regression Analysis to determine the impact of selected factors, including CE indicators, on waste efficiency is detailed below.

Fractional Regression Analysis results. The variables for the Fractional Regression Analysis (FRA) application were defined in the methodology section. The Eurostat database was used as the basic information database for FRA (Eurostat, 2023a, b, c, d, e). The following variables were compared within the analysis: efficiency scores denoted by Non-Hazardous waste (N-H) and Hazardous waste (H), GDPC and GDPR, and selected CE indicators: EMPL, PATENT and INV. Respecting the content limitations of this study, the following section will present results for only three countries in the following order: Bulgaria (the highest demand for waste management enhancement), Slovakia (a country with potential for waste management improvement) and Poland (a country with nearly optimal waste management ratios). The results are presented in *Tables 4, 5* and *6*.

Table 4. Correlation matrix of the Bulgarian variables

	N-H	H	GDPC	EMPL	PATENTS	GDPR	INV
N-H	1						
H	0.74	1					
GDPC	0.92	0.47	1				
EMPL	0.71	0.62	0.73	1			
PATENTS	-0.29	-0.08	-0.52	-0.77	1		
GDPR	-0.15	0.33	-0.49	-0.10	0.34	1	
INV	0.97	0.66	0.92	0.76	-0.32	-0.25	1

Source: *authors' calculations*

Table 4 presents that the first set of variables in the first step of regression model analysis are CE indicators, namely INV and PATENTS. The INV variable is significant b=0.0042, p<0.05 for probit model and b=0.012, p<0.05 for logit model. Marginal effects indicate that a 1% annual increase in investments in the circular economy would result in 1.2% improvement in efficiency for probit and 2% for logit. Patents do not influence the efficiency of the non-hazardous waste management. The model is specified with a linktest - sqfitted p=0.125. All other variables are collinear, and separate models were run for each of them. GDPC is also significant, with a marginal effect of 1.9% for probit and logit model. This result suggests that a 1% increase in GDP per capita leads to a 1.9% improvement in the efficiency of non-hazardous waste management. For the hazardous waste, there are no significant variables in the specified equations. The management of that type of waste was not influenced by the factors affecting non-hazardous waste management.

The results in *Table 5* for Slovakia indicate that the efficiency of non-hazardous waste is weakly related to variables. The only significant variable here is GDPC (b=0.00004 for probit and 0.00008 for logit, linktest p>0.05). The marginal effect of this variable is 2.3%, meaning that a one percent increase in GDPC leads to a 2.3 % increase in efficiency. This is very important result for Slovakia, distinguishing it from other countries in the set. For hazardous waste, investments in circular economy (INV) are a significant variable with a positive marginal effect of 1.4%. This implies that a 1 % improvement in investments in the circular economy leads to a 1.4% improvement in efficiency. This is a positive sign that the country is addressing this waste management problem annually. This result related to the GDPC suggests that the government is actively engaged in addressing hazardous waste management issues responding to them with investments and technologies.

Table 5. Correlation matrix of the Slovak variables

	N-H	H	GDPC	EMPL	PATENTS	GDPR	INV
N-H	1						
H	0.33	1					
GDPC	0.19	0.75	1				
EMPL	-0.20	0.72	0.40	1			
PATENTS	-0.51	-0.63	-0.14	-0.59	1		
GDPR	-0.24	-0.62	-0.65	-0.03	0.08	1	
INV	0.36	0.71	0.86	0.54	-0.41	-0.26	1

Source: *authors' calculations*

Table 6 presents the main factors influencing non-hazardous waste in Poland, which include EMPL, PATENTS, and GDPC. On the contrary, the efficiency of hazardous waste processing is only minimally influenced by most variables, with the exception of GDPR. The first model includes EMPL, which is statistically significant (b=-0.000003 for probit and b=-0.000006 for logit, the linktest p>0.05) and GDPR, which is not significant. The marginal effect of the employment over the non-hazardous efficiency is -30%. This result suggests that a 1% improvement in the number of persons employed in CE sectors reduces efficiency by 30%. All other variables are collinear and are examined by separate models. The other significant variable is INV (b=-0.0004 for probit and b=-0.0003 for logit and linktest p>0.05). This means that investments have a marginal effect on non-hazardous waste efficiency of approximately – 6.4%. Specifically, a 1% improvement in investment will reduce efficiency by -6.4%. The hazardous waste is significantly influenced by almost all variables, but they are collinear and tested by separate regression models. The order of testing follows the value of the correlation coefficient. The following variables influence hazardous waste efficiency with a linktest p-value >0.05 and marginal effects:

- GDPC b=-0.0002 for probit and b=-0.0004 for logit, with marginal effects of -4.6%. Results reveal that a 1% improvement in GDP per capita reduces the efficiency by 4.6%.
- INV b=-0.0003 for probit and b=-0.0008 for logit, with marginal effects of -1.85%. Results reveal that a 1% improvement in investments in the circular economy reduces the efficiency by 1.85%.

All these negative results reveal the focus of the expenditures made in the Polish economy during the research period. They led to improvements in inputs instead of outputs.

Table 6. Correlation matrix of the Poland's variables

	N-H	H	GDPC	EMPL	PATENTS	GDPR	INV
N-H	1						
H	0.18	1					
GDPC	-0.43	-0.91	1				
EMPL	-0.08	-0.92	0.93	1			
PATENTS	0.55	0.63	-0.71	-0.54	1		
GDPR	0.19	0.10	-0.25	-0.17	0.06	1	
INV	-0.54	-0.87	0.91	0.79	-0.82	0.09	1

Source: *authors' calculations*

In the context of research question RQ2, the Fractional Regression Analysis results indicate differences in the mutual influence of GDPC, GDPR, and selected CE indicators (INV, PATENTS and EMPL) on waste efficiency in individual countries. The presented results can be compared with similar studies. By comparing the current results with other research in the field (Marques and Teixeira, 2022) which used different variables for waste management efficiency and fractional regression analysis, it appears that Bulgaria and Poland are more efficient than Slovakia, Czech Republic, and Hungary. This is due to the omission of disposal and incineration in such analysis. This is one of the main contributions of the current study. The novelties of the current study are that its results provide recommendations and reveal deficiencies in waste management within the context of current ecological waste utilization methods. The Fractional regression results are contradictory to those of Marques and Teixeira (2022), mainly due to local effects. The influence of the GDP is similar to their findings (it is almost zero), varying across the investigated countries: positive in some cases, negative in others, and non-existent in certain situations. Ríos and Picazo-Tadeo (2021) conducted similar research, obtaining DEA results that are close to those in the current study. The methodology used by them yielded very low results for efficiency, despite being in line with the current results for Bulgaria. In this paper, GDP has no effect, and the squared GDP has a negative impact, similar to the results for some of the countries in the current study. The current research also highlighted gaps in waste-to-energy management (Halkos and Petrou, 2019). Overall, the waste management sector plays an essential role in achieving the goals of circular economy policies. However, legislative support in the given area, as well as support for national policies and individual state initiatives, are also crucial. The authors Dvorský *et al.* (2023) and also Teplicka and Hurna (2023) addressed the issue of national support and legislative change in the business environment of V4 countries. However, the competitiveness of companies is also an important factor (Musa *et al.*, 2024). Sustainability of economic growth is also an integral part of circular economy principles (Khan *et al.*, 2023). The actual study suggests that government expenditures and policies play a crucial role in waste management efficiency. Countries where governments invest in waste management infrastructure and policies tend to exhibit higher efficiency.

The results regarding PATENTS are controversial and require further in-depth research to establish their connection with resource efficiency. Regarding the study of Platon *et al.* (2022), patents have a positive impact on the circular material use rate in the EU. However, the current paper only partially confirms these results and emphasizes the need for investments in applying patented innovations in the field.

The current study examines the non-oriented DEA approach, contrasting it with other methodologies such as those used by Lacko and Hajduová (2018), which primarily focus on input-oriented models. By doing so, the research area has been enriched with balanced results that can be practically applied. Although the results in the current research differ somewhat from others, they provide a clear picture of waste management efficiency. Importantly, DEA remains unaffected by various variables that might divert attention from the fundamental purpose of the analysis. The study presents results derived from the investigation period and the variables included in the models. These results are confined to the scope defined by the models and the specific variables used. While the results are applicable in their current form, further research is necessary to validate and establish relationships with various processes related to the CE.

Conclusion

The study reveals significant differences between the countries studied, with varying levels of effectiveness and strategic focus on different aspects of waste management. While the Czech Republic has emerged as a notable performer, demonstrating superior performance in waste management practices, other countries such as Bulgaria show lower levels of performance and potential areas for improvement, particularly in adoption of circular economy strategies. The actual study also identifies significant impacts of various factors on the waste management efficiency. Specifically, GDP per capita negatively affects the efficiency of handling hazardous waste due to increased waste production intensity with economic growth. However, the impact is positive for non-hazardous waste, likely due to government expenditures in this area. Employment in the circular economy also positively influences waste management efficiency, indicating the development of the waste processing industry and support for recycling initiatives. Patents in the circular economy demonstrate a positive impact on efficiency, suggesting innovations in waste management practices. Each country exhibits unique characteristics affecting waste management efficiency. For example, the Czech Republic shows a strong influence of patents on hazardous waste management efficiency, suggesting innovative waste management practices in this area. The involvement of the private sector, particularly in Central European countries like Poland and Hungary, plays a significant role in improving waste management efficiency, especially in non-hazardous waste management.

The analysis highlights the importance of policies aimed at promoting recycling and energy recovery, suggesting that investments and advances in circular economy technologies can significantly increase the waste management efficiency. Furthermore, the study highlights the need for tailored approaches to address specific waste management challenges in each country, highlighting the role of long-term policy implementation in promoting sustainable resource management practices across the region. The practical benefit of the study is its repeated application and comparison under the conditions of other countries and also in a different time horizon. The most important finding is that innovations and strategic investments in the circular economy can significantly improve the efficiency of waste management, which is key for sustainable development and ecological stability.

The limiting factor of the subject study is its analysis orientation towards waste management in selected countries within the Central and Eastern Europe region, as well as the analysis of only specific variables in a closed time period and also the non-use of a forecasting model. Therefore, the future research aims to analyse data for all European countries over a longer and actual time horizon, with the possibility of identifying dependencies on other variables and a broader range of circular economy indicators. Future research should also use the model for forecasting the development of the analyzed variables.

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