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Assessment of municipal waste in a circular economy: Do European Union countries share an identical performance?

VERSÃO FINAL APÓS DEFESA

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Dissertação para obtenção do Grau de Mestre em

Economia

(2º ciclo de estudos)

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agosto de 2022

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Identificação: BI14476635
Data: 2022-08-16 às 13:42:44

Acknowledgments

As this year has been quite challenging on several levels and occasions, I would like to express my gratitude to all the people I was lucky enough to come across who have contributed to making it always work out for the best.

First of all, I want to thank my family, especially my parents, brother, and sister, for all the love and support given throughout my life. Thank you for being my biggest supporters and encouraging me to always do and be better than the day before.

The biggest thank you to my boyfriend for all the support and encouragement in the worst and best of times. Thank you for making all the difficulties lighter.

To Professor António Cardoso Marques I wish to express my sincere thanks for all the encouraging conversations, help, and knowledge shared. It was an honour.

Resumo

Os atuais padrões de consumo conduzem à superexploração dos recursos naturais. Quando combinados com estratégias ineficientes de gestão, estes resultam em quantidades incontroláveis de resíduos. Os resíduos municipais destacam-se por serem um produto inevitável da vida quotidiana, que ao conterem uma natureza dispersa, tornam a sua gestão mais complexa. Como ponto central no processo de circularização, a avaliação e consequente identificação dos determinantes dos resíduos municipais torna-se essencial. Contudo, a literatura carece de conhecimentos sobre a monitorização da performance da economia circular. A ausência de um conjunto indicadores estabelecidos para medir os progressos da circularização, torna-o um processo altamente complexo. Este trabalho tem como objetivo preencher esta lacuna através da análise e comparação sistemática do desempenho dos resíduos municipais dos membros da União Europeia no sentido da circularização. Consequentemente, com o intuito de auxiliar na formulação de políticas, fornece mais informações sobre as suas causas. Primeiramente, o método *Data Envelopment Analysis* é usado, onde as variáveis baseadas no quadro de monitorização da Comissão Europeia, juntamente com a representação do consumo de materiais, a preocupação política com a gestão de resíduos, e o estatuto económico dos países, foram os *inputs* e *outputs* utilizados. Com o objetivo de identificar os impulsionadores das performances obtidas, mantendo o equilíbrio entre a componente económica, social e ambiental, recorreu-se ao método *Fractional Regression Models*. A amostra é constituída por 24 países da União Europeia entre 2011 e 2019. Os resultados mostram heterogeneidade entre as performances dos países rumo à circularização, salientando uma barreira entre os países do Norte e do Sul da União Europeia. Os resultados dos *Fractional Regression Models* revelaram que as políticas devem concentrar-se: (i) na melhoria da consciência ambiental através da educação; (ii) nas áreas com menor densidade populacional; (iii) na transição para o consumo de energia proveniente de fontes renováveis; e (iv) no combate do desemprego e pobreza.

Palavras-chave

Desempenho da Economia Circular; Consciência Ambiental; *Data Envelopment Analysis*; União Europeia; *Fractional Regression Models*; Resíduos Municipais.

Resumo alargado

Os atuais padrões de consumo são insustentáveis. A existente superexploração dos recursos naturais, aliada ao contínuo crescimento da população resulta num aumento incessante da degradação ambiental. Como consequência, são geradas quantidades incontroláveis de resíduos. Os resíduos municipais destacam-se por serem uma produção inevitável da vida quotidiana. Ao apresentar uma natureza diversificada, estes resíduos apresentam um processo de gestão mais complexo. Sendo a gestão de resíduos, um pilar essencial da economia circular, este novo modelo económico como solução para as ineficiências do atual modelo económico linear.

O inevitável processo de circularização das economias, apresenta-se como um dos principais desafios enfrentados pelos países e sociedade. A União Europeia ganha particular destaque nesta transição com a crescente atividade política, técnica e científica desenvolvida. Com a ambição de liderar o processo de transição com rumo a uma economia circular, têm sido vários os programas e diretivas desenvolvidos e implementados ao nível da União Europeia.

Como ponto central no processo de circularização, a avaliação e perceção dos impulsionadores da performance dos resíduos municipais numa economia circular são necessárias. Porém, a literatura carece de investigação sobre a monitorização do desempenho dos países no processo da circularização. A ausência de um conjunto de indicadores estabelecidos para medir estes progressos torna-o um processo altamente complexo. Este trabalho contribui para o preenchimento desta lacuna ao realizar uma análise e comparação sistemática do desempenho dos resíduos municipais na implementação da circularização de 24 países da União Europeia, de 2011 a 2019. Consequentemente, fornece mais informações sobre os determinantes da transformação das economias, tendo como objetivo o apoio da formulação de políticas.

Para alcançar o primeiro objetivo a que se propõe, este trabalho usou o método *Data Envelopment Analysis*, usando variáveis baseadas no quadro de monitorização da Comissão Europeia, juntamente com a representação do consumo de materiais, a preocupação política com a gestão de resíduos e o estatuto económico dos diferentes países. Como inputs foram utilizados a geração de resíduos municipais, a despesa geral efetuada na gestão de resíduos, as inovações tecnológicas relacionadas com a gestão de resíduos, o consumo doméstico de materiais e o produto interno bruto. O rácio de circularização e de reciclagem dos resíduos municipais foram os outputs utilizados.

Com a utilização das performances resultantes da primeira fase de análise, foi aplicado o método *Fractional Regression Models*. Tendo como objetivo avaliar os fatores de suporte à economia circular, mantendo o equilíbrio necessário entre a componente económica, social e ambiental. O nível de educação e a percentagem de densidade populacional foram utilizadas para capturar a influência de características sociodemográficas na consciencialização ambiental, que se manifesta na performance economia circular. Acresce, o consumo de energia proveniente de fontes renováveis como parte representativa da componente ambiental. E, por fim, a utilização da componente económica representada pelo nível de emprego e pobreza.

Os resultados detetam a presença de heterogeneidade entre as performances dos países rumo à circularização, salientando uma barreira entre os países do Norte e do Sul da União Europeia. Enquanto que os países do Norte da Europa apresentaram os melhores desempenhos para o período analisado, a generalidade dos países do Sul situam-se aquém da média apresentada pelos restantes. Os resultados dos *Fractional Regression Models* revelaram que as políticas devem concentrar-se: (i) na melhoria da consciência ambiental através da educação; (ii) nas áreas com menor densidade populacional; (iii) na transição para o consumo de energia proveniente de fontes renováveis; e (iv) no combate do desemprego e pobreza.

Abstract

The current consumption patterns are leading to the overexploitation of natural resources. When combined with poor waste management strategies, results in uncontrollable amounts of waste. Municipal waste stands out by being an unavoidable output of our daily lives with a dispersed nature, making its management harder. As a central key in the circularisation process, its assessment and insights into its roots causes are required. However, the literature lacks knowledge on monitoring the circular economy. The lack of a universally accepted set of indicators to measure the progress towards circularisation makes it a highly complex process. This paper fills in the gap, by performing a systematic analysis and comparison of the municipal waste performance of the European Union countries towards circularisation. Consequently, it provides further insights into the root causes. Firstly, it involves the employment of the Data Envelopment Analysis. The variables based on the monitoring framework from the European Commission paired with the representation of the consumption of materials, the political concern with waste management, and the economic status of the countries were the inputs and outputs used. Secondly, by using the Fractional Regression Models, we aim to study the determinants' scores, focusing on maintaining a balance between economic, social, and environmental components. Our sample is formed by 24 European Union countries from 2011 to 2019. Results showed a non-homogeneity in countries' performances towards circularisation, highlighting a gap among Northern and Southern European Union members. Fractional Regression Models' findings revealed that policies should concentrate on: (i) the improvement of environmental awareness through education; (ii) areas with lower population density; (iii) the transition towards the consumption of energy from renewable energy; and (iv) the fight of the unemployment rate and level of poverty.

Keywords

Circular Economy Performance; Data Envelopment Analysis; Environmental Awareness; European Union; Fractional Regression Models; Municipal Waste.

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Acronyms List

BCC	Banker, Charnes & Cooper
CCR	Charnes, Cooper & Rhodes
CE	Circular Economy
CLogLog	Complementary LogLog
CMUr	Circular Material Use rate
DEA	Data Envelopment Analysis
DMC	Domestic Material Consumption
DMUs	Decision-Making Units
EU	European Union
FRM	Fractional Regression Models
GDP	Gross Domestic Product
MW	Municipal Waste
RrMW	Recycling rate of Municipal Waste
WM	Waste Management

1. Introduction

Today's society's model based on 'make, take and dispose' is unsustainable. A linear economy model leads to the incessant exploitation of resources resulting in uncontrollable amounts of waste (UNDP, 2019). The unremitting population growth backed up by the unsustainable consumption patterns, provokes the growth of indirect environmental pressures (EEA, 2014; Levaggi et al., 2020). Increasing amounts of waste allied to poor Waste Management (WM) results in air pollution, climate change, water, and soil contamination, interfering with several ecosystems and species (EEA, 2014). In 2019, the 28 EU members released almost 2,8 thousand tonnes of carbon dioxide from WM (Eurostat, 2021a).

As an alternative to the inefficient traditional linear economy model, the European Union (EU) is committed to move towards a Circular Economy (CE). Therefore, the circularisation process is being accompanied by the intensification of the political, technical, and scientific activity within the EU. With the Waste Framework Directive 2008/98/EC (European Commission, 2008), the crucial role of WM in the transition to a CE was established, stipulating that WM prioritises the reduction of generated waste. Disposal should only be considered when no other option is available. In 2018, these intentions were reinforced by the Directive (EU) 2018/851, where concrete targets were established, such as the percentage of Municipal Waste (MW) by weight being recycled and prepared for re-use (European Union, 2018).

In 2015, a CE package was created to make the circularisation process as efficient as it can be. In this package, the targets were directed to the prevention of, reuse, and recycling of waste. Despite these efforts, the average amount of MW generated by EU countries has increased in the past few years (Eurostat, 2021b). Therefore, the European Commission reinforced its ambition to enhance the circularisation process by adopting a new Circular Economy Action Plan in 2020. It established the need for a profound transformation to achieve the CE (European Commission, 2020b). However, despite all this common guidance from the EU, do its members perform identically?

This research contains several contributions to the advancement of CE, both in academia and practice. It sheds light on the assessment of the performance of the 24 EU members into circularisation through the employment of the Data Envelopment Analysis (DEA). Once the performance of the EU countries is known, it raises the question of what determinants are behind the performances? The knowledge of these factors is essential for policymaking. By applying the Fractional Regression Models (FRM), we aim to study the determinants' scores, having into attention the balance necessary between the economic, social, and environmental factors.

The economic agent is a fundamental part of the problem as well as part of the solution and cannot be left out of the CE transition assessment. The power held by consumer choices can ramp up the CE if well used. However, the CE research presents a distinct lack of studies combining a range of socio-economics factors (Kravchenko et al., 2020). Consequently, in our contribution to the literature, we attempt to include more social variables without undermining the equilibrium necessary within the social, economic, and environmental components of the CE. For the employment of the DEA, the following inputs were used: MW generated, general expenditure on WM, innovation on WM-related technologies, Domestic Material Consumption (DMC), and Gross Domestic Product (GDP). The recycling rate of MW (RrMW) and the circular material use rate (CMUr) were taken as outputs for the period 2011 to 2019. For the FRM, the explanatory variables used were the unemployment rate, the level of education, a measure of poverty, population density, and the consumption of energy from renewable sources.

The contribution of this work is twofold. Firstly, it involves the employment of the DEA to assess the progress towards the circularisation of EU members' economies. Recurring to the combination of the variables based on the monitoring framework COM(2018) 29 with the consumption of materials, the political concern with the WM, and the economic status of the countries. Secondly, this work contributes by explaining the countries' performance, and to this end, it innovates by applying the FRM to determine its drivers. In the first stage, a non-homogeneity among EU members was obtained, being the southern members the worst performers. The FRM analysis proved a positive impact of education level, population density, and the consumption of energy from renewable sources on the DEA scores. Being the impact of the last, only noticed on the inefficient countries. Unemployment and poverty, as expected appeared to be a slowdown of countries towards a CE.

The remainder of this paper is divided into the following sections: (2) Literature Review, (3) Policy context on European Union Members, (4) Data and Methodology, (5) Results and Discussion, and (6) Conclusion.

2. Literature Review

If we maintain our current lifestyle, by 2050, will be necessary the resources of three earths to satisfy humankind's needs (European Parliament, 2021). The current pattern of resource exploitation is provoking the production of, on average, five tonnes of waste from each European citizen per year (European Commission, 2021). Although only a small part of the total waste generated concerns the MW in the EU (half a tonne per capita), due to its diverse nature, it is more difficult to treat, requiring special attention (Marino & Pariso, 2020). WM takes a central role in the solutions in the transition from a linear economy to a CE, as established by the European Commission (2020). With increasing legislation, action plans, and frameworks leading the way for EU members, CE is a hot topic in literature.

The assessment of CE performance has been realized recurring to diverse methods[1], such as: (i) Life Cycle Assessment (Gbededo et al., 2018); (ii) Multi-criteria approaches and fuzzy logic (Kazancoglu et al., 2018); (iii) Design for X and guidelines (Sassanelli et al., 2020); (iv) Data Envelopment Analysis and Input-Output models (Expósito & Velasco, 2018; Giannakitsidou et al., 2020); (v) Material Flow Analysis (Millette et al., 2019); and (vi) Emergy- and exergy- based approaches (Wang et al., 2021).

The use of DEA is well established for the evaluation of many environmental aspects (Callao et al., 2019). DEA is a linear programming tool used to evaluate the performances of the commonly named Decision-Making Units (DMUs), in this specific case, countries. The main advantage of its use is that it can be applied without any data distribution and in the presence of several variables (inputs and outputs). In turn, it is possible to introduce a social component into the analysis (Lee & Ji, 2009).

In the literature, DEA has been applied in studies of CE and WM either for individual countries or sets/ panels of countries. Focusing on EU studies, Callao et al. (2019) and Halkos & Petrou (2018) concluded that a disparity existed among the members. Regarding the choice of outputs and inputs, there is no established guideline pointed out by the literature. While some authors used waste recycled (Sarkis & Dijkshoorn, 2007), others used variables related to costs (Huang et al., 2011), or even emissions (Chen et al., 2010) as

[1] See Sassanelli et al. (2019) for a more detailed revision of methodologies used in the assessment of circular economy performance.

outputs. Meanwhile, for the input choice De Jaeger et al. (2011) used the percentage of old and young people, and Sasao (2016) the number of workers in WM.

The literature lacks knowledge on assessing the progress of circularisation maintaining a balance between the economic, social, and environmental components. Resulting from the challenging nature of the social factor, its incorporation into the analysis of CE remains largely uncovered (Kravchenko et al., 2020). Society engagement, sensibility, and behaviour assume a crucial role in the success of the CE transition (European Commission, 2019). Indeed, consumer behaviour is fundamental to the success of any circularisation process. Ultimately this transition hinges on behaviours and consumption preferences. Nevertheless, tracking consumption patterns and their inclusion in the analysis of CE is highly complex.

Along with the assessment of the CE, also the interest of the literature on the determinants of the circularisation process took shape. By clarifying or encouraging the implementation of policies targeted at the drivers and barriers identified, we are one more step closer to the CE and its benefits (Tan et al., 2022). Maintaining an equilibrium between the social, economic, and environmental components, Neves & Marques (2022), concluded that among EU countries, environmental regulation, environmental awareness through education, and increases in the recycling rate contribute to the circularisation process. Throughout the analysis of the 27 EU countries, Busu (2019) results showed that resource productivity and the use of renewable energy act as factors to improve CE. As for Robaina et al. (2020), results showed that an increase in environmental taxes provokes a negative effect on resource productivity (proxy used for the measurement of the CE). The negative impact of the environmental taxes on the Gross Domestic Product (GDP) is more significant than the impact on material consumption. The lack of consensus in the literature, despite increasing efforts for a thorough identification of the determinants of a CE, generates the need for more research on the topic (de Jesus & Mendonça, 2018).

This research contributes to the fulfilment of this gap by (i) performing a systematic analysis and comparison of the MW performance of EU countries towards circularisation considering the consumption of materials, the political concern with WM, and the economic status of countries, and (ii) get further insight into its root causes. Therefore, this work contributes to the literature by proposing the fullest possible assessment of CE and the evaluation of the factors that support the circularisation process without undermining the use of the economic, social, and environmental factors.

3. Policy context on European Union Members

The EU is committed to transforming the economies of its members into circular ones. Such evidence is present in the rising legislation among EU countries regarding WM and CE. The Waste Framework Directive 2008/98/EC, considered by the European Commission (2008) as an essential legislative document, is taken as a starting point. With this legislative document, an order of preference on WM was established, known as the WM hierarchy. Where the fundamental aspect of the WM approach starts by reducing the amount of waste generated simplifying the remaining processes. If waste cannot be prevented, there is a need for its reuse or recycling. In case of none of the above options is implemented, the disposal option arises, and the EU members should see it as the last instance (European Commission, 2008).

The Circular Economy Package was created in 2015 with the primary goal of closing the loop and transforming the circularisation process as efficiently as possible. In this action plan, the targets were directed towards the first three steps presented by the WM hierarchy (preserve, reuse, and recycle), that way avoiding the last one (disposal). Two specific measures are, among others, recycling 65% of MW by 2030 and recycling 75% of packaging waste by 2030 (European Commission, 2015).

In 2018, the European Commission reinforced its intentions through Directive (EU) 2018/851, which amended the Directive 2008/98/EC. There were defined new targets, such as the preparation for the reuse and recycling of MW should increase to 55% by weight by 2025. In 2030 the percentage should be 60%, and in 2035 should be to a minimum of 65% by weight (European Union, 2018).

Despite the efforts made, the average amount of MW generated by the EU countries has continued to increase. Reaching the amount of 513 kilograms per capita in 2019 (Eurostat, 2021b). Therefore, the European Commission reinforced its ambition to achieve circularisation by adopting a new Circular Economy Action Plan in 2020. This plan appears as one of the main pillars of the European Green Deal. Establishing the need for a profound transformation to achieve the circularisation of economies (European Commission, 2020).

To scrutinize the progress of EU members towards circular economies, the European Commission put together a Monitoring Framework for CE based on ten indicators grouped into four key aspects (i) Production and consumption, ii) WM, iii) Secondary raw materials, iv) Competitiveness, and Innovation) (European Commission, 2018). Along with this monitoring project, the European Commission is also developing an assessment framework to include consumer behaviour in the CE analysis. Denominated as ‘consumer footprint’, this framework, monitors the average environmental impact of consumer behaviour, which when applied to a country scale, is known as ‘consumption footprint’ (European Commission, 2017).

4. Data and Methodology

This section describes the database used (4.1) as well as the methods employed (4.2). In subsection 4.1, along with the identification of the data used, there is a brief presentation of its key aspects.

4.1. Data

To evaluate the annual CE performance of EU members, focused on MW, the DEA was used, followed by the FRM (methods explained in a more detailed way in the next sub-sections). The present study is composed of a panel of 24 countries from 2011 to 2019[2]. The temporal horizon used is justified by the data availability. Table 1 summarizes the variables used, their abbreviations, and sources.

Table 1. Description of the variables used.

Variables	Abbreviation	Source
Data Envelopment Analysis		
Outputs		
Recycling Rate of Municipal Waste, % of the total municipal waste generated	RrMW	Eurostat
Circular Material Use Rate, % of total material use	CMUr	Eurostat
Inputs		
Municipal Waste generated, kilograms *pc*	MWG	Eurostat
General expenditure on WM, million euro *pc*	GOV	Eurostat
Innovation in WM-related technologies, number	INNO	OECD
Domestic Material Consumption, tonnes *pc*	DMC	OECD
Gross Domestic Product, *pc* (constant 2015 US$)	GDP	World Bank
Fractional Regression Models		
Dependent variable		
DEA scores	Scores	
Independent variables		
Unemployment, total (% of the total labour force)	UNEMP	World Bank
Population with tertiary education, % of the population between 25 and 64 years	EDU	PORDATA
Percentage of the population living on less than $5.50 a day	POV	World Bank
Population density (persons per square kilometre)	DENS	Eurostat
Share of energy from renewable sources, % gross final consumption of electricity	REN	Eurostat

[2] Given the last year under assessment, the United Kingdom is still considered for our study.

Notes: *pc* denotes *per capita*, OECD denotes Organisation for Economic Co-operation and development, UNESCO UIS denotes United Nations Educational, Scientific and Cultural Organization Institute for statistics.

Within the first stage of analysis, the recycling rate of MW (RrMW) measures the percentage of the total MW generated that is recycled (Eurostat, 2021c). The Circular material use rate (CMUr) measures the share of material recovered and reintroduced into the economy. A higher percentage indicates that there is more secondary material substituting the primary raw materials (Eurostat, 2021d). The MW generated (MWG) includes all the waste generated by economic activities, plus households (Eurostat, 2021e). Domestic Material Consumption (DMC) is given by the difference between the direct material input and the exports. It is defined as the total amount of resources an economy uses (Eurostat, 2021f).

Given the complexity of CE, the European Commission has been monitoring the ongoing circularisation process of the economy. As a result of this monitoring framework, a set of ten indicators were defined and divided into four groups: (i) Production and consumption, (ii) Waste management, (iii) Secondary raw materials, and (iv) Competitiveness and Innovation by European Commission (2018). Each group comprises essential indicators to capture the key elements of CE. Table 2 specifies the ten indicators comprised in their respective stage.

Table 2. Ten indicators resulting from the monitoring framework COM(2018)29.

(i) Production and consumption	
	a) EU self-sufficiency for raw materials
	b) Green Public Procurement *
	c) Waste generation
	d) Food waste *
(ii) Waste management	
	e) Overall recycling rate
	f) Recycling rates for specific waste streams
(iii) Secondary raw materials	
	g) Contribution of recycled materials to raw materials demand
	h) Trade in recyclable raw materials
(iv) Competitiveness and innovation	
	i) Private investments, jobs and gross value added
	j) Patents

Notes: * denominates the indicators under development.
Source: Adapted from the COM(2018)29.

Within the first group, indicator a) is only specified by the type of material and not by countries, making indicator c) the only one used (given by the MWG). In the second group, only indicator e) was used under the form of the RrMW. The focus of this paper is on MW, so indicator f) was discarded. In group iii), indicator g), given by CMUr, was chosen over indicator h), defined by trade in recyclable raw materials. The CMUr is more suitable for our study as it is more wide-ranging since it already captures in its calculation the movements measured by the trade in recyclable raw materials. In the final group, indicators i) and j) (Eurostat, 2021g, 2021h, respectively) were excluded from this analysis since they would limit our database, both in time and number of countries. However, a proxy given by the innovation on WM-related technologies in number was introduced.

Adding to the previous indicators the DMC, the general expenditure on WM (GOV), and the GDP were introduced. As recognized by the European Commission (2020b), the consumer plays a key role in CE transition and holds the power to ramp it up. To incorporate the effect of consumption in this work, the DMC was introduced, aiming to capture the link between CE and the consequences of consumer empowerment (Marino & Pariso, 2020). The GOV indicator reflects the efforts put in by governments on WM resolution. Finally, the GDP captures the economic situation of the DMUs under analysis.

On the FRM employment, the level of education and the population density were introduced, aiming to capture the influence of individual and socio-demographic characteristics on environmental awareness and, therefore, on WM performance in a CE (Triguero et al., 2016). As argued by several authors, its appears to be a positive link between literacy and environmental awareness (Neves & Marques, 2022). Therefore, this study uses the percentage of the population that has tertiary education as a proxy for the literacy rate. As established by Weisz et al. (2006), there is a tendency for stress population density results in an inferior consumption of materials. One of the reasons given is the need to make more efficient use of the materials, as it becomes scarcer in an area with greater demand.

The unemployment rate and the level of poverty were chosen to compose the economic component, as they are inevitable products of the functioning of the economy and translate simultaneously the generation of inequalities. As obtained by Neves & Marques (2022), poverty and income inequality constitute a barrier to the circularisation process.

As a representation of the environmental component, the consumption of energy from renewable sources was introduced. As two main pillars of the sustainable future, renewable energy is expected to impulse the CE, and vice versa.

4.2. Data Envelopment Analysis Method

The DEA was first introduced by Charnes et al. (1978). It is a linear programming tool used for performance measurement on homogeneous units called DMUs. Please note that our DMUs are the 24 EU countries. This non-parametric approach estimates a production frontier constructed from the observed inputs and outputs. The distance of each DMU from this frontier constitutes their level of efficiency. DMUs on the frontier are efficient, obtaining a score equal to one, whereas the others are considered inefficient. As the distance from the frontier increases, so does the inefficiency associated with the DMU.

As is well known, two standard DEA models, the CCR, (Charnes, Cooper & Rhodes, 1978) and the BCC (Banker, Charnes & Cooper, 1984), are available, differing between them in the returns to scale assumption. The CCR approach measures the performance of the DMUs assuming constant returns to scale, while the BCC approach introduces the variable returns to scale. Regarding the orientation of the model, it can be input orientated (minimises inputs without requiring additional outputs) or output orientated (maximises outputs using the same amount of each input). Considering the aim of this work, the results are presented using the output orientated analysis by recurring to the CCR model. These options seem to be more appropriate given the data under analysis (EU members with harmonised goals and guidelines), and the research question (measure the performance of countries).

Thereby, the relative efficiency of DMU_j is given by a weighted sum of outputs divided by a weighted sum of inputs represented by approach (1):

$$\max \quad P_j = \frac{\sum_{r=1}^{q} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \qquad (1)$$

subject to

$$\begin{cases} P_j = \dfrac{\sum_{r=1}^{q} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad (j = 1, \ldots, n) \\ \mu_r \geq 0 \ (r = 1, \ldots, q), \quad v_i \geq 0 \ (i = 1, \ldots, m) \end{cases} \qquad (2)$$

Where, P_j is the performance that we are trying to measure, with $j = 1, \ldots, n$ representing the countries under study. Each country uses m inputs and q outputs, which implies that the input vector is represented by $x_{ij} = x_{1j}, \ldots, x_{mj}$ and that $y_{rj} = y_{1j}, \ldots, y_{qj}$, represents the output vector. Finally, μ_r and v_i are the weight vectors, attributed to the outputs and inputs. The DEA allows each DMU to combine its set of weights that maximise its efficiency (Charnes et al., 1978). By reducing equation (1) to a linear programming form, also known as the Charnes-Cooper transformation, considering the output orientation, the equation (3) comes as follows:

$$\max P_j = \sum_{r=1}^{q} \mu_r y_{rj} \qquad (3)$$

subject to:

$$
\begin{cases}
\sum_{r=1}^{q} \mu_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \quad (j = 1, \dots, n) \\
\sum_{i=1}^{m} v_i x_{ij} = 1 \\
\mu_r \geq 0 \ (r = 1, \dots, q), \quad v_i \geq 0 \ (i = 1, \dots, m)
\end{cases} \tag{4}
$$

Given the goal of assessing EU countries' performance of WM in a CE and given the advantages of the endogenous attribution of weights and lack of data assumptions, the use of the DEA method reveals suitable.

4.3. Fractional Regression Models

With the use of the FRM, issues like the correlation between the variables used in the DEA analysis and the second stage are avoided (Ramalho et al., 2010). The FRM was proposed by Papke & Wooldridge (1996) to deal with explained variables within the interval [0,1], such as the DEA efficiency scores (y). To achieve the desired constraints on the conditional mean of y, the FRM approach requires that y follows a functional form. This assumption is given by:

$$E(y|x) = G(x\theta) \quad (5)$$

Where x is a vector of k environmental factors, θ is the vector of parameters to be estimated, and $G(.)$ is a nonlinear function within the interval [0,1]. As proposed by Papke & Wooldridge (1996), it is used the Quasi-Maximum Likelihood based on the Bernoulli log-likelihood function to estimate the FRMs, given by:

$$LL_i(\theta) = y_i log[G(x_i\theta)] + (1 - y_i) log[1 - G(x_i\theta)] \quad (6)$$

Where the Quasi-Maximum Likelihood estimator θ is defined by:

$$\hat{\theta} \equiv arg \max_{\theta} \sum_{i=1}^{N} LL_i(\theta) \quad (7)$$

Within the FRM, there are the one-part and the two-part models, differing in the assumption of the impacts of the environmental, economic and social factors on the different DMUs. The two-part models allows the analysis of the efficient DMUs (y=1) and the relative efficiency of inefficient DMUs $(y < 1)$ separately. In turn, the two-part model should be used when there is the suspicion that the environmental, economic and social factors do not have an equal impact on all DMUs. The first part of this model expresses the probability of observing an efficient DMU (y=1), through a binary indicator (z) that assumes a value equal to one for efficient DMUs and a value between]0,1[for inefficient DMUs. The conditional probability of observing an efficient DMU is given by:

$$Pr(z = 1|x) = E(z|x) = F(x\beta_{1P}) \quad (8)$$

Where β_{1P} is a vector of variable coefficients and F(.) represents a cumulative distribution function (Ramalho et al., 2010). According to Papke & Wooldridge (1996), the more usuals cumulative distribution functions used to model binary data are the logit, probit, loglog, and complementary loglog (cloglog). The second part of the two-part models is estimated using only the DMUs with a DEA score between $]0,1[$:

$$E(y|x, y \in]0,1[) = M(x\beta_{2P}) \quad (9)$$

The FRM is more suitable to deal with the DEA due to the absence of assumptions on the conditional distribution of DEA scores or heteroskedasticity patterns and for being estimated by Quasi-Maximum Likelihood. Among the FRM, the two-part models have some advantages when compared to the one-part models, since it allows the analysis of i) the differences between the efficient and inefficient DMUs and ii) the distance of the inefficient DMUs from the efficiency frontier (the relative efficiency of inefficient DMUs) (Ramalho et al., 2010).

5. Results and Discussion

The following section comprises in the first subsection, a brief analysis of the descriptive statistics followed by the results of the DEA and the FRM methods. In the second subsection, there is a deeper analysis and interpretation of the results with policy recommendations.

5.1. Results

At first glance, the descriptive statistics (Table 3) appear to appoint for the non-homogeneity of the performance rhythms among the EU countries. Indeed, by analysing the maximum and minimum values for the variables, there is a significant gap between the EU members.

Table 3. Descriptive statistics.

	Mean	Std. Dev.	Min.	Max.	Obs.
CMUr	9.1315	6.4766	1.3	30	216
RrMW	37.977	14.123	9.7	67.2	216
MWG	481.88	125.17	247	862	216
GOV	8E-05	7E-05	5.71E-06	0.0002	216
INNO	51.974	69.749	0.33	344.42	216
DMC	16.137	6.1792	7.9989	34.361	216
GDP	32718.24	21241.03	6461.114	4583.7	216

Note: Max. – Maximum; Min. – Minimum; Std. Dev. – Standard deviation; Obs. – Observations.

In 2011, for the CMUr, only 10 of the 24 EU countries were above the average. In 2019, Austria and Slovenia joined the previous group, and Finland pulled out. The Netherlands was always the country with the highest score, hitting its highest value in 2019 (30%). A downward trend over the years was presented in Bulgaria, Ireland, and Romania. Focusing on the RrMW, the country to reach the highest rate was Germany, with 67.2% in 2019. Meanwhile, the lowest recycling rate was registered by Latvia (9.7% in 2011), followed up by Lithuania and Slovakia. However, these countries reverted their position, moving above the 24 EU average in 2019. Far behind the rest of the EU countries were Greece and Romania (21% and 11.5 %, respectively, with the average being 39.9% in 2019).

On the inputs side, Denmark was the country that generated the most MW (844 kg pc in 2019), followed by Luxembourg. On the opposite side was Romania (280 Kg pc in 2019). Only 9 of the 24 EU members presented, in 2019, lower values for the MW generated than the one registered in 2011. From which it is the reduction of The Netherlands that stands out the most (from 568 to 508 kg pc). Moving on to general expenditure on WM, only 7 countries were above the EU average in 2019. From these, the United Kingdom presented the highest expenditure on WM, although Italy showed the sharpest growth during the period. Concerning the innovation variable, Germany stands out from the rest of the countries under analysis, reaching its highest value in 2011 with 344 innovations in WM-related technologies. Finally, the country with the biggest DMC during the entire period was Finland. While the lowest values, in 2019, were registered by The Netherlands, Spain, and the United Kingdom.

The results of CE performance (Table 4) are in line with the non-homogeneity among EU countries pointed out by the descriptive statistics.

Table 4. DEA scores.

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Austria	80.3	86.8	81.0	82.4	84.3	85.4	84.8	81.9	82.3
Belgium	92.5	95.6	94.8	97.8	**100**	97.5	99.7	**100**	**100**
Bulgaria	**100**	**100**	97.1	85.9	96.3	**100**	**100**	93.0	**100**
Czech Republic	54.4	67.4	69.7	71.8	76.9	81.9	73.6	71.9	75.4
Denmark	**100**	58.9	43.6	61.4	54.8	58.6	65.1	50.1	83.3
Finland	94.9	**100**	71.2	57.7	66.0	67.9	70.9	62.5	72.6
France	63.5	64.9	65.6	67.6	70.3	74.6	79.8	74.6	82.5
Germany	81.5	89.3	82.9	83.9	84.4	85.2	**100**	88.4	87.3
Greece	31.0	32.3	29.1	27.6	28.9	31.8	37.6	37.5	41.3
Hungary	76.0	87.9	87.9	80.7	85.2	93.8	96.7	95.3	88.0
Ireland	48.9	58.5	61.6	85.8	72.1	59.9	57.1	53.0	55.0
Italy	58.2	69.9	77.0	81.8	85.0	87.2	88.0	93.2	92.0
Latvia	43.8	39.4	68.6	78.5	74.8	90.5	81.9	60.2	83.4
Lithuania	57.4	66.0	66.1	**100**	89.5	99.9	99.0	**100**	92.4
Luxembourg	**100**	**100**	87.8	75.0	80.4	83.3	86.8	**100**	79.3
The Netherlands	95.7	**100**	**100**	97.2	**100**	**100**	**100**	97.7	**100**
Poland	77.4	88.1	**100**	**100**	**100**	**100**	95.3	93.9	91.8
Portugal	35.3	49.0	51.8	69.0	58.9	55.3	50.6	48.8	51.5
Romania	49.1	59.0	52.6	50.2	48.0	46.6	45.1	35.5	35.2
Slovakia	59.4	45.8	61.5	70.6	53.8	58.6	65.9	73.8	79.7
Slovenia	73.9	**100**	94.8	84.7	**100**	**100**	**100**	99.7	**100**
Spain	56.3	60.2	60.9	57.6	53.8	59.7	62.0	60.6	64.0
Sweden	82.3	81.9	84.5	89.4	84.5	86.2	82.4	84.1	85.4
United Kingdom	69.6	68.5	69.3	69.4	69.0	70.0	71.2	72.5	80.8
Average	70.1	73.7	73.3	76.1	75.7	78.1	78.9	76.2	79.3

When looking at the average values of the 24 EU countries for each year, in table 4, there is an upward trend with some exceptions (2013, 2015, and 2018). Furthermore, given the use of the output-oriented DEA, the difference between maximum efficiency and the average results for each year can be interpreted as the amount of possible improvement of the output without requiring any additional inputs. In 2011, for the average performance of the 24 countries, the outputs could increase by 29.9% with the same amount of inputs, while in 2019, they could grow by 20.7%.

Along with the non-homogeneity among the EU Countries, it is possible to verify some fluctuations in terms of CE performances tied to some countries. Notorious positive variations are visible in Latvia, Lithuania, and Slovakia. Meanwhile, negative position changes were registered in Finland, Luxembourg, and Romania. The scores with maximum efficiency (100%) are highlighted (in Table 4) and were achieved by 9 countries. However, Belgium, Bulgaria, and The Netherlands achieved the best performances when considering the full-time span. Furthermore, Figure 1 presents the average DEA scores for each DMU (the 24 EU countries) for the average of the entire period (2011 to 2019).

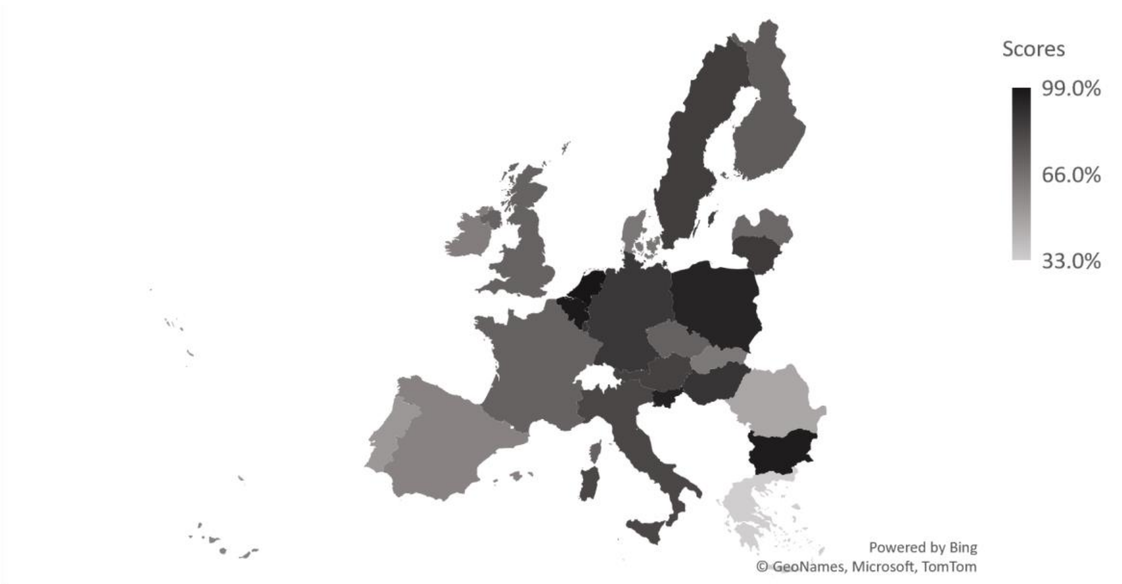

Figure 1. DEA average scores for the 24 countries.
Source: Own elaboration.

With figure 1, it becomes clearer, the existence of non-homogeneity among countries' performances. In general, exists a barrier between the northern and southern European countries' performance. The southern EU members have the worst performances in the implementation of the CE. Moreover, with some exceptions, a geographic proximity effect appears to exist, where neighbouring countries have similar performance levels.

Looking to assess the drivers behind the CE performance, in the second stage of the analysis, the FRM was applied. As referred, the most common FRM specifications to model binary data are the logit, probit, loglog, and cloglog. Following Ramalho et al. (2010), fundamental tests were applied to choose between these different specifications that can lead to different outcomes. The RESET test detects if there are misspecifications on the general function form (H_0: the model has a correct specification). The P-test allows the comparison of nonlinear regression models, where the possible outcomes are: (i) the rejection of one model and the non-rejection of the other; (ii) the rejection of both models; and (iii) the non-rejection of both models. Finally, the GOFF-I, GOFF-II, and GGOFF (Generalised Goodness-of-functional form) tests were also applied. The results of the FRM specifications subject to the RESET, P and GOFF-I, GOFF-II, and GGOFF are in table A.1. In short, regarding the one-part models, the specifications tests showed that the specifications loglog and cloglog are more suitable since none of the null hypotheses were rejected. In the first part of the two-part models, we conclude that the logit is the most adequate FRM specification. For the second stage of the two-part models, the results pointed out to the cloglog specification. Thereby, the results of the FRM are presented in Table 5.

Table 5. Estimation results for selected FRM.

	One-part models		Two-part models	
			First part	Second part
	Loglog	Cloglog	Logit	Cloglog
UNEMP	-0.0480429***	-0.0272243***	-0.0299799	-0.0242157***
EDU	0.022360***	0.0128471***	0.0775319**	0.0099252***
POV	-0.0286084***	-0.0150135**	0.0537971	-0.0194865***
DENS	0.0045341***	0.0022915***	0.00601**	0.0022333***
REN	0.0075299	0.0046139	-0.0291351	0.0076***
Cons.	-0.8075299	-0.7716103**	-8.510174**	-0.7013314**
Obs.	216	216	216	185
R^2	0.39137909	0.38695615	0.11635244	0.40555348

Notes: Cons. denotes the constant, Obs. denotes the number of observations, and ***,**,* denote 1%, 5%, and 10% level of significance, respectively.

The first striking point to emerge from the results displayed in Table 5 is that the signals and magnitudes of the variables, when statistically significant, tend to be consistent, proving the robustness of the findings. Regarding the significances, the change in the share of energy consumed from renewable sources stands out. This determinant of the CE performance only assumes a positive impact in explaining the relative efficiency of the inefficient DMUs. Meaning that the consumption of renewable energy can be seen as an important driver to improve the circularisation process among inefficient countries.

Comprehensive to all models, it is clear that investment in education and areas with higher population density conduce to greater performances towards a CE. Population with higher education is more propane to adopt circular strategies, while a higher population density results in lower consumption of resources, contributing therefore to the implementation of

CE. In its turn, unemployment and poverty provoke a negative impact, as expected, on the implementation of circularisation.

Due to the non-homogeneity detect among DEA scores, it could be expected that the two-part models would be more appropriate, as it allows a segmented analysis between the efficient countries and those that are not. However, as established, all the countries under analysis present common guidelines and frameworks regarding the implementation of the circularisation process. Being this a possible reason why there are no major changes among the two types of models under analysis.

5.2. Discussion

The use of the DEA seems to have been appropriate. Indeed, this method, by being frontier oriented, instead of central tendencies oriented, is highly relevant for the analysis of efficiency. This kind of analysis makes it possible to incorporate various relationships that are left uncovered by other methods. Adding to this advantage is the possibility to attribute endogenous weights resulting in an allocation of free preferences and the introduction of several inputs and outputs without any assumption on data distribution (Lee & Ji, 2009), leading to the choice of the DEA method on the first stage.

The DEA findings show the existence of significant gaps among the EU members. While the best results belong to the northern and central EU countries, the worst scores were primarily registered in the southern EU members. Latvia, Lithuania, and Slovakia registered under the period, a noteworthy launch from bottom places to performances above the EU average. Greece, Portugal, and Romania were the bottom three worst performers during the entire period. Moreover, only 9 countries, for the entire period of analysis, were above the performance averages, proof of the non-homogeneity among EU members, in line with the literature (Giannakitsidou et al., 2020; Marino & Pariso, 2020).

Looking at the path of The Netherlands, this country's performance may have been actively influenced by policies after 2016. Each year from 2016 to 2019, the Netherlands government launched a new program to lead the Dutch economy towards a circular one. Of these programs, the Raw Materials Program in 2017, stands out. The government, together with the industry, established how they were going to move their economy to run only with renewable resources. Their objective is to achieve, by 2030, a reduction of 50% in raw materials consumption and, in 2050, become a free-waste economy (Government of the Netherlands, 2021), showing that this country, besides being well positioned on the DEA results, also has the ambition to improve.

From the FRM application, we conclude that the level of education and population density contribute to an increase in a country's efficiency, being these results in line with the literature (Neves & Marques, 2022; Robaina et al., 2020; Weisz et al., 2006). Policies directed to the improvement of the conditions of well-being and information (resulting from education) contribute to the circularisation process. The introduction of educational subjects focused on environmental best practices would result in the younger generations being more aware of these subjects. In turn, once enlightened, young people may be able to influence the older ones to adopt best practices. As identified by Neves & Marques (2022), these have a more willing to adopt CE. In areas with lower population density, is necessary to raise awareness of the rationale use of the materials. Such goal can be achieved through better urban planning in the countries. Policies to encourage housing for less populated areas, among other goals, helps to combat differences in population densities, resulting in more rational use of materials created by the increase in demand.

Concerning the economic component, this paper's findings revealed that unemployment (Heshmati & Rashidghalam, 2021) and the level of poverty (Neves & Marques, 2022) decreased the countries' performance towards CE, as established by literature. As part of one of the Sustainable Development Goals, the reduction of inequalities and poverty is imperative, not only for the achievement of the circularisation of economies but as well to the accomplishment of the well-being of populations. The CE can be seen as a solution for the creation of more sustainable and inclusive growth among countries. Policies should focus on attracting more investment into sustainable industries and circular business models, creating green jobs as an output (Sulich & Sołoducho-Pelc, 2021).

As result of the Ambiental concern, the findings of this work conclude that the consumption of renewable energy has a positive impact on the increase of inefficient countries' performances. By having the objective of transforming the economies' model into a sustainable one, within the energy sector the CE is focused on renewable energy. As seen by Petković et al. (2021) and Robaina et al. (2020), the consumption of energy from renewable sources acts as a driver for the CE. Therefore, policies oriented to the energy transition will, consequently, influence the transition towards circularisation.

This paper aims to enhance the existing literature, firstly through the analysis of EU members' MW performance into circularisation and considering a comprehensive inclusion of essential indicators. Secondly, it added the further step of finding the drivers behind the EU countries' performance by employing the FRM. Through the application of the FRM, it was established that education and population density are fundamental drivers to improve the performance of EU countries towards circularisation.

As in all studies of this kind, there are limitations, and in this one, it was the short time span used as well as the data and indicators available, making it impossible to analyse all the EU members with the indicators proposed by the European Commission.

6. Conclusion

This study proposed an MW performance assessment in the context of the circularisation of the EU economies. A CCR output-oriented approach was applied to 24 EU countries. A large disparity between the EU members was observed regarding their efficiency in achieving circularisation through WM. Indeed, despite all the efforts put in by the EU, the response by the various countries appears inconsistent. Countries just starting on the road towards a CE should take the footsteps of the best performers.

In the second stage, with the DEA scores, the FRM was applied to find the determinants of efficiency. Little changes implemented in every household resulting from more education/ information provoke significant changes on the whole. When allied with policies targeted at raising the living standard, a better geographical distribution of the population, and the consumption of energy from renewable sources, a better performance of the EU countries towards CE is achieved.

Further investigations should focus on analysing national strategies of the best and worst performers. Furthermore, if more years become available, they should be included in the analysis. A closer look should be kept on the consumer footprint indicator development, and if possible, its introduction in the analysis can only be positive. Moreover, a geographic proximity effect appears to exist, where neighbouring countries have similar performance levels, perhaps through the implementation of similar practices. This possible effect could be analysed using spatial econometrics.

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Appendix

Table A.1. Specification tests.

	One-Part Models				Two-part Models							
					First part				Second part			
	Logit	Probit	**Loglog**	**CLoglog**	**Logit**	Probit	Loglog	CLoglog	Logit	Probit	Loglog	**CLoglog**
RESET test	0.627	0.873**	**0.264**	**0.522**	**0.872****	0936***.	0.938***	0.846**	0.681	0.525	0.905**	**0.202**
GOFF-I	0.993***	0.848**	**---**	**0.546**	**0.883****	0.850**	---	0.787*	0.538	0.543	---	**0.211**
GOFF-II	0.788*	0.967***	**0.419**	**---**	**0.497**	0.914**	0.916**	---	0.623	0.467	0.993***	**---**
GGOFF	0.414	0.224	**0.419**	**0.546**	**0.095**	0.148	0.916**	0.787*	0.624	0.440	0.993***	**0.211**
	P-test											
H1:FRM II- Logit	---	0.544	**0.565**	**0.637**	**---**	0.758*	0.978***	0.630	---	0.760*	0.896**	**0.240**
H1: FRM II- Probit	0.331	---	**0.329**	**0.522**	**0.473**	---	0.903**	0.691	0.966***	---	0.970***	**0.205**
H1: FRM II-Loglog	0.956***	0.901**	**---**	**0.529**	**0.423**	0.690	---	0.420	0.569	0.527	---	**0.212**
H1: FRM II- CLoglog	0.500	0.886**	**0.318**	**---**	**0.377**	0.790*	0.893**	---	0.766*	0.516	0.968***	**---**

Notes: ***,**,* denote 1%, 5%, and 10% level of significance, respectively. The values presented are the p-values.