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Meeting the challenges of the waste hierarchy: A performance evaluation of EU countries

Giovanna D'Inverno [a,b,*], Laura Carosi [a], Giulia Romano [a]

[a] Department of Economics and Management, University of Pisa, Via Ridolfi 10, 56124 Pisa, Italy
[b] Faculty of Economics and Business, KU Leuven, Naamsestraat 69, 3000 Leuven, Belgium

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ABSTRACT

The focus of this paper is to evaluate how well European countries are advancing towards a Circular Economy transition and to which extent they are fulfilling the European Union (EU) requirements in terms of municipal waste management. With this aim, an innovative composite indicator is devised by integrating the Goal Programming Synthetic Indicator (GPSI) methodology with the Analytic Hierarchy Process (AHP). The suggested methodology allows to encompass not only the guidelines provided by the EU directives and the EU Waste Hierarchy, but also the deviations from the EU thresholds. As a first step of the analysis, a dashboard of indicators is identified together with a set of targets that European countries are supposed to meet. Indicators, targets and their relative importance in the dashboard have been discussed and validated by a team of experts. Then, two Goal Programming Synthetic Indicators are computed taking into account two different perspectives. The first one rewards the countries with good performance in the higher level of the Waste Hierarchy, while the second one penalizes countries whose infringements are in the lower part of the Waste Hierarchy. Hence two different systems of aggregating weights are identified by means of the Analytic Hierarchy Process and accordingly two scenarios are explored. The analysis is performed using Eurostat data on 28 European countries from 2013 to 2018. For each year, countries are assessed in terms of their ability to keep the right waste management track delineated by the Waste Hierarchy principles. Countries' ranking over time is first obtained and then interpreted in light of countries policies and achievements, deriving policy suggestions to improve waste management strategy able to reach the expected results.

1. Introduction

The EU Waste Hierarchy establishes a priority order among waste management actions: first of all 'Prevention', then 'Preparing for re-use', 'Recycling', 'Recovery' and lastly 'Disposal'. It grounds its roots in 1979 Lansink's Ladder (Lansink, 2018) and since 2008 it has become a strategic pillar of the European waste management legislation. The Waste Framework Directive 2008/98/EC (WFD) identified the EU Waste Hierarchy as the road map for European waste management. Countries were supposed to enact and implement policies to decrease the level of waste generation ('Prevention') and to foster waste treatment actions related to the higher part of the hierarchy ('Preparing for re-use' and 'Recycling' are preferred to 'Recovery' and 'Disposal'). With the promulgation of the Circular Economy Package in 2015 and the subsequent related Directives, the EU Waste Hierarchy still maintained its importance (Domenech and Bahn-Walkowiak, 2019). The paradigm shift for a more circular economy led the European legislator to adopt ambitious environmental targets which are strictly related to the EU Waste Hierarchy priority order: minimum levels for recycling rates were required together with a maximum threshold for landfilling. Nowadays, the European Commission, in cooperation with the European Environment Agency, is working to monitor countries' deviations from the fixed waste targets and to provide a system of early warning to help national governments in meeting their commitments (see for example the assessment project proposed by The European Environment Information and Observation Network -https://www.eionet.europa.eu).

In line with the interest of the European legislator, we believe there is room for further analysis, integrating the institutional monitoring activity. In this perspective, we aim at evaluating the ability of European countries to be on the right waste management track towards a Circular Economy transition and towards a shift to the upper tiers of the EU Waste Hierarchy (Egüez, 2021). Our research question finds a strong

* Corresponding author at: Department of Economics and Management, University of Pisa, Via Ridolfi 10, 56124 Pisa, Italy.
E-mail addresses: giovanna.dinverno@unipi.it (G. D'Inverno), laura.carosi@unipi.it (L. Carosi), giulia.romano@unipi.it (G. Romano).

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motivation also from the pressing need of European and national authorities to observe a number of waste dimensions and to evaluate countries' actions in its complexity. To address this issue, for each EU Waste Hierarchy's tier, we identify a set of indicators and correspondingly a set of thresholds. Our choices have been discussed and validated by a team of experts. Unlike previous works, countries' performances are evaluated along two complementary aspects of the considered indicators: the deviation from the threshold and its importance with respect to the EU Waste Hierarchy. Given the policy relevance of representing all the dimensions with a single index in a multi-criteria framework, composite indicators turn out to be a useful tool to aggregate several indicators and shed lights on the overall performance in a comprehensive way (Luzzati and Gucciardi, 2015; Rogge et al., 2017). In line with the main focus of the paper, we suggest a composite indicator encompassing priorities and deviations from targets. More precisely, it combines two methodologies which are naturally linked to the above research question: the Goal Programming Synthetic Indicator (GPSI) methodology and the Analytic Hierarchy Process (AHP). The GPSI methodology has been introduced by Blancas et al. (2010) and then profitably applied to address sustainability issues (Lozano-Oyola et al., 2012; Molinos-Senante et al., 2016; Pérez et al., 2018). It borrows from Goal Programming the goal notion as deviation from a given threshold level (see for all Charnes and Cooper (1961) and Ishizaka and Nemery (2013)). Deviations are computed to detect the strengths and the weaknesses of the evaluated countries. As in Blancas et al. (2010), deviations regarding strengths and weaknesses are respectively aggregated in two composite indicators and then included in an overall index, namely the GPSI. As concerns the aggregating weights, AHP is a useful tool to represent the preferences and to derive priority weights (see for all Saaty, 1990; Ishizaka and Nemery, 2013; Pakkar, 2014). In the present analysis, the weights are developed so to reflect different priorities along the Waste Hierarchy's tiers and to aggregate the chosen performance indicators in the GPSI.

Our contribution to the existing literature and to the current debate on waste management assessment is threefold (for recent reviews we refer to Argoubi et al. (2020),Schilkowski et al. (2020) and Chioatto and Sospiro (2022), among others). First, we propose an innovative tool that enables EU countries' waste management performance evaluation in a more comprehensive way. It takes into account not only the guidelines provided by the EU directives and the EU Waste Hierarchy, but also the deviations from the EU thresholds. This constitutes an enhancement with respect to previous approaches where only the hierarchy relevance was mostly emphasised. From a methodological point of view, we suggest a composite indicator that uses the AHP to elicit the priorities over waste management actions and the GPSI to aggregate the deviations. While there are several contributions that combine AHP with goal programming techniques (see for example Aznar et al., 2011; Ho and Ma, 2018, and the references therein), to the best of our knowledge, this is the first proposal integrating the AHP and GPSI methods. Second, we consider different systems of weights to aggregate the deviations, unlike standard GPSI applications where only one system of weights and hence only one type of aggregation is foreseen. By doing so, we emphasize the fact that deviations related to the country's strengths and deviations related to country's weaknesses may have different scale of importance[1]. Third, our paper takes part in the debate on how to measure European countries' compliance with the EU Waste Hierarchy (Castillo-Giménez et al., 2019; Pires and Martinho, 2019; Egüez, 2021; Zhang et al., 2022). While the existing contributions exclude the highest level of the hierarchy and take into account just waste treatment actions, our analysis considers also waste prevention, thus offering a systemic perspective. We show the practical use of the proposed methodology by evaluating the EU-28 countries waste management from 2013 and 2018. The obtained results are relevant to inform EU and national authorities about successful strategies and actions still needed for the lagging countries.

The remainder of the paper is organized as follows. In Section 2 we briefly describe the European waste management legislation and outline the recent literature dealing with the EU Waste Hierarchy. In Section 3 we present the methodology, highlighting the added value of combining the AHP and GPSI approach. In Section 4 we implement the proposed approach and detail the empirical application step by step, giving particular attention to the information obtained from the discussion with the panel of experts. In Section 5 we discuss the obtained results, critically comparing the findings arising from two different scenarios and showing the relevance of the proposed tool from a policy-making perspective. In the last Section, we conclude giving some examples of good practices as emerged from the analysis and sketching ideas for future research.

2. The EU Waste Hierarchy and a brief related literature

The EU Waste Hierarchy principle defines a rank among the waste management actions, taking into account their environmental impact and their role in safeguarding citizens' well being. This concept was introduced in the '80s but implemented in the EU legislation only with the 2008 Waste Framework Directive (WFD) and in the United Nations 'Agenda 2030' with the Sustainable Development Goal 12 in 2016 (Van Ewijk and Stegemann, 2016). By establishing a new legal framework for managing waste in the EU, the Directive 2008/98/EC delineated a clear waste hierarchy as reported in Fig. 1, that put at the first step waste 'Prevention', as the preferable way to avoid waste treatment at all.

Then, the EU placed 'Preparing for re-use', as a way to use again goods for other processes and users, and 'Recycling' to recover materials as secondary materials in a circular process. 'Recovery' and 'Disposal' in landfills were put at the bottom of the hierarchy, as the last choices for waste management, to be reduced as much as possible and the least preferred ones over the other solutions.

The Directive stated the polluter-pays principle and extended producer responsibility (EPR), affirming that waste producers must be responsible and bear the costs of waste management. Further, the Directive required that National Authorities defined waste management and prevention plans together with recycling and recovery targets to be achieved by 2020. Ten years later, the amending Directive (EU) 2018/851 was included in the EU Circular Economy Package aiming at moving the EU in a straightforward path towards a circular economy, overcoming the linear model. In this line, the EU adopted a long-term vision to waste management, able to increase recycling and limiting landfilling and incineration. Indeed, the Directive (EU) 2018/851 enhanced the request for waste prevention efforts and established new recycling targets for municipal waste so that at least 55%, 60%, and 65% of municipal waste by weight should be recycled by 2025, 2030, and 2035,

Fig. 1. EU Waste Hierarchy. *Source*:https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-.Directive_en.

[1] For a similar approach in a Goal Programming framework see Aznar et al. (2011).

respectively. Moreover, the Directive required the separate collection of bio-waste (or recycling at source) by 2024 and of textiles and hazardous waste by 2025. To incentivize strategies that encompass the Waste Hierarchy, landfill and incineration charges, separate collection and pay-as-you-throw schemes are encouraged.

With reference to packaging waste, the EU approved the Directive 94/62/EC on packaging and packaging waste, that was then amended by the Directive 2018/852/UE, also included in the Circular Economy Package. The EU aimed at preventing the generation of packaging waste and at encouraging the re-use, recycling and recovery of packaging in line with the approved Waste Hierarchy. Indeed, EPR schemes for all kind of packaging materials should be established by the end of 2024 and specific targets for recycling were defined, including an overall target for all packaging (65% by 2025 and 70% by 2030). Referring to specific materials contained in packaging waste, the Directive set the following targets: for paper and cardboard 75% by 2025 and 85% by 2030, for plastic 50% by 2025 and 55% by 2030, for wooden 25% by 2025 and 30% by 2030, for glass 70% by 2025 and 75% by 2030, for ferrous metals 70% by 2025 and 80% by 2030, for aluminium; 50% by 2025 and 60% by 2030. EU countries vary significantly in terms of waste generation and waste treatment policies and strategies (Romano et al., 2021). As highlighted by Egüez (2021), each country decides and applies waste treatment plans in a path dependent way, considering its culture, tradition and social norms, but also considering different treatment costs. For these reasons, EU Directives stressed the relevance of incentives and penalties to encourage a proper application of the Waste Hierarchy.

As highlighted by the EU, in countries with a waste intensive energy production, the overall recycling rate is highly dependent on the management of the energy-related waste types (Eurostat, 2019). Thus, policy decisions about how to treat waste have an impact on the results obtained regarding the perspective and progresses achieved in the transition towards circular economy (Romano et al., 2021). Moreover, the EU Directive 2018/850 capped the maximum amount of municipal waste landfilled at 10% by 2035 [2]. At the same time, it affirmed that reduction of landfilling should avoid the development of excessive capacity for the treatment of residual waste facilities, such as through energy recovery, as this could undermine the achievement of the Union's re-use and recycling targets. Indeed, for strategy planning, economic costs should be counterbalanced by the trade-off with environmental and social impact of different choices, looking to the synergistic achievement of economic, social, and environmental results (Minoja and Romano, 2021) and to the increasing relevance of eco-efficiency estimation in urban waste management (Romano and Molinos-Senante, 2020; Llanquileo-Melgarejo et al., 2022), that incorporates economic and environmental variables in performance estimation (Schaltegger and Sturm, 1989; Yu et al., 2020). Looking at the lowest tier of the Waste Hierarchy, the Directive sets a clear limit for future landfilling, but it does not address the issue of the existing stored waste (Machiels et al., 2019). Actually an amendment on landfill mining was proposed by the European Parliament, but the final version of the Directive 2018/850 did not include this proposal. Therefore, landfill mining is not specifically regulated although it is not prohibited, if carried out in line with the EU legislation on waste. Regarding the scientific debate on the environmental impact of the existing landfill reduction and the landfill mining, see for example (Machiels et al., 2019; Pehme et al., 2020; Blengini et al., 2019; Einhäupl et al., 2021). In the recent literature few papers have compared waste management performance of EU countries in terms of their compliance with the EU Waste hierarchy. Nevertheless, they address different research questions and accordingly, they use different techniques with respect to the present paper (we refer to the literature review in Castillo-Giménez et al. (2019),Egüez (2021) and Chioatto and Sospiro (2022) for previous works). Castillo-Giménez et al. (2019) assess the convergence among EU countries in the treatment of the municipal waste during the period 1995–2016 (similarly on convergence, also Marin et al. (2018)). The authors propose a Data Envelopment Analysis (DEA) composite indicator to avoid subjectivity in the sub-indicators aggregation and they overcome the well-known ranking issues in DEA by using the system of common weights as proposed in Despotis (2005). Even if they do not clearly mention the EU Waste Hierarchy concept, they take into account landfill, incineration, recycling and composting as treatment operations. As their main focus is on waste treatment, they do not deal with prevention, that is the highest level of the EU Waste Hierarchy. Their analysis denotes a marked convergence since the introduction of the Waste Framework Directive in 2008 and shows that the worst performing countries are those that mostly rely on landfill. Central and Northern EU members show better performance than Mediterranean and in particular Eastern European countries.

On the contrary, the papers by Pires and Martinho (2019) and Egüez (2021) consider directly the concept of EU Waste Hierarchy. Pires and Martinho (2019) propose a Waste Hierarchy Index (WHI) applied to municipal solid waste using circular economy principles for the EU countries in 2014. They determine the weights to aggregate the sub-indicators in a subjective way, based on how waste operations contribute to the circular economy, and provide alternative scenarios. Their analysis finds an average negative WHI indicator, concluding that EU Waste Hierarchy has not been implemented correctly to promote circular economy so far. Egüez (2021) constructs a Waste Hierarchy Compliance Index of the EU countries for the period 2010–2016. Also in this work, the weights are exogenously assigned and different scenarios are foreseen. The author regresses the index on stringency and enforcement of environmental regulation, which are found to have a positive effect on the compliance index. Although Egüez (2021) and Pires and Martinho (2019) evaluate the European Countries in the EU Waste Hierarchy's perspective, the prevention action is still not included in their analysis. With respect to these recent works, our paper differs in a number of aspects. First, we evaluate the performance of the EU-28 countries taking into account the European Union requirements for waste management, not only in terms of priorities as suggested by the EU Waste Hierarchy, but also in terms of set targets' achievement. Second, to aggregate the sub-indicators in compliance with the EU Waste Hierarchy, we use weights obtained using the Analytic Hierarchy Process so to represent the institutional debate and the preferences elicited by an interviewed panel of experts. To this extent, we foresee different weighting systems for the fulfillment of the set thresholds, depending on whether this occurs at the upper or lower tiers of the hierarchy. Third, we consider a systemic perspective, where not only waste generation is considered, but also waste prevention, with important implications when it comes to policy instrument recommendations.

3. Methodology

In this paper we evaluate the European countries' waste management performance by means of a composite indicator, taking into account the guidelines provided by the EU directives and the preferences expressed by a panel of experts. With this aim, we construct a composite indicator by integrating the methodology proposed by Blancas et al. (2010) with the Analytic Hierarchy Process. Specifically we proceed in four steps, briefly introduced below and summarized in Fig. 2.

Step 1. We identify the focus of our analysis in the evaluation and eventually in the comparison of the European countries' waste management performances. We adopt several criteria and sub-criteria taking into account the European legislation and, in particular, the EU Waste Hierarchy. More precisely, criteria are related to the actions described in the EU Waste Hierarchy. Associated with each sub-criterion a suitable indicator is chosen, together with a threshold (also called aspiration

[2] This commitment was originally supposed to be fullfilled by 2030 and then moved to 2035 in the final drawing-up of the Directive.

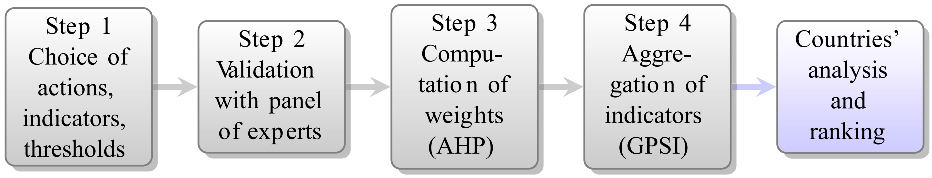

Fig. 2. Four steps to construct a composite indicator and evaluate the European countries' waste management performance.

level) the countries are supposed to meet.

Step 2. The choice of the indicators and of the corresponding thresholds is then validated by a panel of experts that have different roles and different points of view in the waste management framework. Experts are interviewed and they are asked to express their priorities for the chosen criteria and sub-criteria using the Saaty's 1–9 fundamental scale. Moreover, they are asked to evaluate the adequacy of the chosen indicators and their corresponding thresholds, with respect to the actions under assessment. After the experts' validation, a dashboard of indicators is determined.

Step 3. Using the AHP methodology, experts' opinions about the criteria priorities are gathered in a pairwise comparison matrix and, accordingly, a system of weights for criteria is derived. The same procedure is performed to construct a system of weights for the sub-criteria belonging to the same criterion (for more details see Section 3.1).

Step 4. For each country and for each indicator, the deviation from the established threshold is computed. All deviations are then suitably aggregated in a Goal Programming Synthetic Indicator (GPSI). As each deviation is related to a given sub-criterion, it "contributes" to the value GPSI according to the importance of the associated sub-criterion, that is, according to the corresponding weights determined in Step 3 (for more details see Section 3.2).

Hereinafter we discuss the AHP and GPSI method, respectively for the computation of the weights and for the aggregation of the waste performance indicators.

3.1. An AHP approach for the computations of weights

As observed in the review paper by Vaidya and Kumar (2006, p.2), "*the speciality of AHP is its flexibility to be integrated with different techniques like Linear Programming, Quality Function Deployment, Fuzzy Logic, etc. This enables the user to extract benefits from all the combined methods, and hence, achieve the desired goal in a better way.*" (for a recent discussion, see also Tavana et al. (2021)). In particular, when it comes to the construction of composite indicators, AHP is a very useful operational tool to elicit the preferences of decision makers and/or experts and to derive priority weights (see for all the review papers provided by Pakkar, 2014; Pakkar, 2015). The developed weights are then used either to aggregate the performance indicators or to restrict the importance of each indicator with respect to the other ones (see for example Chen, 2002; Basso and Funari, 2020; Wu et al., 2022). In line with the first approach, we use the AHP method to develop priorities for the chosen criteria and sub-criteria and to aggregate the chosen performance indicators using the derived priorities as weights. The AHP method, originally introduced by Saaty (1977), requires pairwise comparison judgments on the importance of criteria and sub-criteria. For any given couple of criteria or sub-criteria, a Decision Maker (DM) is asked to evaluate their relative importance and to define the intensity of such importance. Judgements are translated in numbers on the basis of the Saaty 1–9 scale, reported in Table 1 (see for example Ishizaka and Nemery (2013)).

Given n criteria (or sub-criteria), the Decision Maker's pairwise comparison matrix A is built according to his/her preferences. The matrix A is an $n \times n$ positive matrix, whose diagonal elements a_{ii} are

Table 1
Saaty's 1–9 fundamental scale.

Intensity of importance	Definition
1	**Equal importance**
2	Weak
3	**Moderate importance**
4	Moderate plus
5	**Strong importance**
6	Strong plus
7	**Very strong or demonstrated importance**
8	Very, very strong
9	**Extreme importance**

equal to 1 and $a_{ij} = \frac{1}{a_{ji}}$ for every $i, j \in \{1 \ldots n\}$ such that $i \neq j$. As Saaty (2003) observes, cardinal inconsistency is more common than cardinal consistency. Actually, a Decision Maker can find difficulties in assigning an exact value of his/her preferences and in preserving the ordinal transitivity. Therefore, a consistency check is needed (see for all Mu et al., 2020). Saaty (1990) shows that A is consistent if and only if its principal eigenvector λ_{max} is equal to the matrix order n and in general $\lambda_{max} \geqslant n$. Due to the difficulties of making a perfectly consistent judgment, a certain degree of inconsistency can be accepted. Inconsistency is measured by computing the following ratio $\frac{IR}{CR}$, where IR is the matrix A inconsistency ratio $\frac{\lambda_{max} - n}{n-1}$ and CR represents the coefficient of random inconsistency which is computed by calculating IR for randomly filled reciprocal matrices (see for all Franek and Kresta, 2014). If $IR > 0.1$, the inconsistency is judged unacceptable and the DM is asked to revise his/her evaluations. Once a consistent matrix A is obtained, the normalized principal eigenvector is computed and its components are the priority weights of the evaluated criteria (or sub-criteria).

In the current analysis, the decision process involves a panel of experts rather than a single Decision Maker, so that it is necessary to aggregate their individual judgements. As the experts are separately interviewed and they have the same importance inside the panel, we aggregate their individual pairwise comparison matrices in a unique matrix, encompassing all the judgments. Following a very common approach (Aczél and Saaty, 1983), we derive the global matrix by taking the geometric mean of the experts' pairwise comparison matrices. As Saaty and Vargas (2007) underline, geometric mean preserves reciprocity and satisfies the homogeneity condition. Nevertheless, to consider the global matrix reliable, the individual matrices should not be too dispersed. To establish whether the level of the observed dispersion is acceptable, we run the statistical test proposed by Saaty and Vargas (2007). For a comprehensive discussion on the aggregation issue, the reader can refer to Mu et al. (2020) and Amenta et al. (2021).

3.2. A GPSI approach for the aggregation of indicators

Step 4 of our methodology basically follows the one proposed by Blancas et al. (2010). These authors propose to create a composite indicator by borrowing the notion of goal from Goal Programming (see for all Charnes and Cooper (1961) and Ishizaka and Nemery (2013)). Given a set of indicators, a set of corresponding aspiration levels (thresholds) is determined. When values greater than the fixed aspiration level are preferred, the indicator is classified as positive, while as negative in the opposite case.[3] Similarly to the Goal Programming, a goal for each indicator is defined by means of its deviation from the aspiration level. Blancas et al. (2010) underline that the aspiration level of each indicator has to be established by a panel of experts. In our analysis, the aspiration levels are identified by the European Directive thresholds. Regarding the goals for which the European legislation hasn't fixed a threshold yet, specific aspiration levels have been designed taking into account the general principles of the Waste Directive Framework, experts' opinion and the current institutional debate (see Section 4.1 for more details). Following the same notation of Blancas et al. (2010), we consider m indicators and n countries to be evaluated. J and K represent the set of positive and negative indicators respectively. Accordingly, for a given country i, I_{ij}^{+} is the value of the positive indicator $j \in J$ and I_{ik}^{-} is the value of the negative indicator $k \in K$. The aspiration level (i.e. the threshold) for the positive indicator j is denoted by u_j^{+}, while u_k^{-} represents the aspiration level for the negative indicator k. Whenever $I_{ij}^{+} \geqslant u_{ij}^{+}$ and $I_{ij}^{-} \leqslant u_{ij}^{-}$, the country i fulfills the established requirements, while the opposite inequalities highlight the country is negatively deviating from good performance. In case of a positive indicator $j \in J$, we have

$$I_{ij}^{+} + n_{ij}^{+} - p_{ij}^{+} = u_{ij}^{+}, \quad \text{with} \quad n_{ij}^{+}, p_{ij}^{+} \geqslant 0, \quad n_{ij}^{+} \cdot p_{ij}^{+} = 0,$$

where n_{ij}^{+} and p_{ij}^{+} denote the negative and the positive deviation respectively.

If the value of I_{ij}^{+} is greater than u_{ij}^{+}, it is $p_{ij}^{+} > 0$, $n_{ij}^{+} = 0$ and the indicator is related to a strength of the country i (see also Molinos-Senante et al., 2016; Lozano-Oyola et al., 2012; Pérez et al., 2018). On the other hand if the value of I_{ij}^{+} is lower than u_{ij}^{+}, it is $p_{ij}^{+} = 0$, $n_{ij}^{+} > 0$ and the indicator is related to a weakness of the country i.

In case of a negative indicator $k \in K$ we have

$$I_{ik}^{-} + n_{ik}^{-} - p_{ik}^{-} = u_{ik}^{-}, \quad \text{with} \quad n_{ik}^{-}, p_{ik}^{-} \geqslant 0, \quad n_{ik}^{-} \cdot p_{ik}^{-} = 0$$

where n_{ik}^{-} and p_{ik}^{-} denote the negative and the positive deviation respectively.

As before, if the value of I_{ik}^{-} is greater than u_{ik}^{-}, it is $p_{ik}^{-} > 0$ and $n_{ik}^{-} = 0$, but symmetrically to the positive case, the indicator is related to a weakness of the country i. On the other hand if the value of I_{ik}^{-} is lower than u_{ik}^{-}, it is $p_{ik}^{-} = 0$, $n_{ik}^{-} > 0$ and the indicator is related to a strength for the country i.

It is worth noticing that the similarity with the Goal Programming is only related to the goals representation as no optimization problem is involved in the analysis.[4] Once the goals' deviations have been computed for every indicator, two Goal Programming Synthetic Indicators are constructed. The first one is denoted by $GPSI^{S}$ and it aggregates the deviations which describe the country's strengths. The second indicator is denoted by $GPSI^{W}$ and it collects the deviations related to the country's weaknesses. A positive level of $GPSI_i^{S}$ suggests that country i is on a good track: it exhibits values over the thresholds for the positive indicators and values under the thresholds for the negative ones. On the other hand, a positive level of $GPSI_i^{W}$ reveals that country i has weaknesses with respect to the indicator system, as it has values under the thresholds for the positive indicators and values over the thresholds for the negative ones.

In both indexes, each deviation is divided by the corresponding aspiration level, so to perform a suitable normalization, and then it is multiplied by a given weight. Therefore, for every country i we get

$$GPSI_i^{S} = \sum_{j \in J} \frac{w_j p_{ij}^{+}}{u_j^{+}} + \sum_{k \in K} \frac{w_k n_{ik}^{-}}{u_k^{-}}$$

and

$$GPSI_i^{W} = \sum_{j \in J} \frac{w_j n_{ij}^{+}}{u_j^{+}} + \sum_{k \in K} \frac{w_k p_{ik}^{-}}{u_k^{-}}$$

where $w_j, j \in J$ and $w_k, k \in K$ denote the weights for the positive and the negative indicators respectively. According to Blancas et al. (2010), the system of weights is given *a priori* by a panel of experts and/or by the involved stakeholders. In several applications the same importance is assigned to each analyzed dimension, so that weights are the same for each indicator (see for example Lozano-Oyola et al., 2012; Molinos-Senante et al., 2016; Pérez et al., 2018). In the current analysis the system of weights is constructed by means of the AHP methodology (see also Section 3.1). Finally, similarly to Blancas et al. (2010), a global composite indicator is built so to aggregate the strengths and the weaknesses of each country. For every country i, we get

$$GPSI_i = \alpha GPSI_i^{S} - \beta GPSI_i^{W} \tag{1}$$

where α and β are the relative weights for the two composite indicators. Whenever strengths and weaknesses have the same importance, Blancas et al. (2010) suggest to set $\alpha = \beta = 1$, such that $GPSI_i$ is simply the difference between $GPSI_i^{S}$ and $GPSI_i^{W}$.

4. Empirical Analysis: Municipal waste management evaluation

4.1. Step 1. Choice of actions (criteria), indicators and thresholds

To evaluate to which extent European countries fulfill the European Union requirements in terms of waste management, we use Eurostat data from 2013 to 2018 for the EU-28 countries. The ability of a country to keep the right track towards a Circular Economy transition and towards a shift to the upper tiers of the EU Waste Hierarchy (Egüez, 2021) is measured by comparing the country's performance with a set of a suitable thresholds. From 'Prevention' to 'Disposal', several representative indicators have been identified, classified with respect to the tiers of the EU Waste Hierarchy and eventually chosen in line with data availability and information availability on the set thresholds. As remarked in Pires and Martinho (2019), there might be difficulties in measuring waste prevention and especially preparing for re-use. Due to data availability, the lack of specific targets for the action 'Preparing for re-use' and the strict relationship between 'Preparing for re-use' and 'Recycling', these two actions are treated as a unique macro-category, namely 'Preparing for re-use and recycling' in this analysis. Table 2 summarises the chosen indicators, along with their definition, the Waste Hierarchy tier they belong to and the Eurostat code. The third column of the table lists the threshold levels associated with each indicator and the fourth shows the references to the legislation and to documents relevant for the thresholds' choice. In the last column, an indicator is classified as positive if greater values than the fixed target are preferred to lower values and as negative in the opposite case (Blancas et al., 2010).

Going into details, we identify two indicators for 'Prevention' actions. The first one follows the guidelines provided by *Zero Waste Europe*, a non-governmental organization (NGO) promoting the zero waste strategy in Europe both at municipal and international level. This organization has proposed to complement the European legislation (Condamine, 2020) with stringent provisions about 'Prevention'. Specifically, it suggests an overall waste reduction target defined as a residual waste maximum cap, so to reward waste generation decreases. As the focus of the 'Prevention' action is the global amount of non-recyclable municipal waste, a kg/per capita target is preferred to a

[3] Blancas et al. (2010) consider also neutral indicators. As our analysis does not deal with neutral indicators, for the sake of brevity we omit them in the methodology description.

[4] For this aspect see also the discussion in Blancas et al. (2010).

Table 2
Indicators and EU targets for Waste Hierarchy.

Waste hierarchy	Indicator	Targets by 2030	Targets' source	Definition	Eurostat code on waste	Type of indicator
Prevention	Residual waste/pro capita (kg)	⩽120 kg	a	The tonnage of residual waste (sent to incineration with and without energy recovery and to landfill) divided by the population.	[RCV_E]+ [DSP_I]+ [DSP_L_OTH]	Negative
Prevention	Circular material use rate	⩾19%	b	Share of material recovered and fed back into the economy - thus saving extraction of primary raw materials - in overall material use.	[SDG_12_41]	Positive
Preparing for re-use & recycling	Recycling rate of municipal waste	⩾60%	c	The tonnage recycled from municipal waste divided by the total municipal waste arising.	[SDG_11_60]	Positive
Preparing for re-use & recycling	Packaging rate	⩾70%	c	Total quantity of recycled packaging waste divided by the total quantity of generated packaging waste.	[W1501]	Positive
Preparing for re-use & recycling	Paper and cardboard packaging rate	⩾85%	c	Total quantity of recycled packaging waste divided by the total quantity of generated packaging waste (only paper).	[W150101]	Positive
Preparing for re-use & recycling	Plastic packaging rate	⩾55%	c	Total quantity of recycled packaging waste divided by the total quantity of generated packaging waste (only plastic).	[W150102]	Positive
Preparing for re-use & recycling	Wooden packaging rate	⩾30%	c	Total quantity of recycled packaging waste divided by the total quantity of generated packaging waste (only wood).	[W150103]	Positive
Preparing for re-use & recycling	Glass packaging rate	⩾75%	c	Total quantity of recycled packaging waste divided by the total quantity of generated packaging waste (only glass).	[W150107]	Positive
Recovery	Energy recovery rate	⩽35%	d	The tonnage of waste sent to incineration with energy recovery divided by the total municipal waste arising.	(R1) [RCV_E]	Negative
Disposal	Landfill rate	⩽10%	c	The tonnage of waste sent to landfill divided by the total municipal waste arising.	(D1-D7, D12) [DSP_L_OTH]	Negative

Source: Authors' own elaboration on Eurostat data. About the targets:
a) Zero Waste Europe Policy Briefing 2020;
b) https://eu-dashboards.sdgindex.org/map/indicators/sdg12_circular/trends, https://ec.europa.eu/commission/presscorner;
c) EU Waste Framework Directive - Directive 2008/98/EC, Directive (EU) 2018/850, Directive (EU) 2018/851, Directive (EU) 2018/852, https://www.europarl.europa.eu;
d) Residual to recycling rate of municipal waste.

percentage reduction target. As in Condamine (2020) the suggested target by 2030 is 120 kg/capita of non-recyclable municipal waste, we adopt accordingly this threshold for our analysis. The second indicator is the circular material use rate (see also Table 2) and and it belongs to the set of EU Sustainable Development Goal (SDG) Indicators. It has been conceived to evaluate progress towards SDG 12 ('Responsible consumption and production') and it can be seen as part of the global SDG indicator 11.6.1 'Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated by cities'. According to the new Circular Economy Action Plan (CEAP), there is a strict relationship between waste prevention and high values of circular material use rate (Bianchi and Cordella, 2023). As long-term and ambitious objective, the European Commission has set the minimum level of circular material use rate at 19%.

Referring to the macro-category 'Preparing for re-use and recycling', we consider the municipal recycling rate, the recycling packaging rate and the mono-material recycling rates of paper, plastic, woods and glass. For this class of indicators, the corresponding thresholds are the targets to be achieved by 2030 by all Member States, as set in the EU Waste Framework Directive. The chosen indicator for 'Recovery' is the energy recovery rate. Currently, European Directives don't foresee any specific target, although the European Parliament has recently called on the Commission to propose binding targets (European Parliament, 2021). In the attempt to tackle the countries' performance in the most comprehensive way, we propose a target following the rationale underlying the general principles of the Waste Directive Framework to be submitted to experts' validation. As a communication of the European Commission (2015) underlines, waste to energy is the most preferable option only when the higher Waste Hierarchy actions can not be implemented. Moreover, a subsequent communication of the European Commission (2017) specifies that waste-to-energy capacity should be delineated "to avoid potential economic losses or the creation of infrastructural barriers to the achievement of higher recycling rates". Therefore, we set a target level for this indicator as residual of the other waste management activities. Since the European Countries are supposed to recycle at least 60% of municipal waste and that a small percentage to set landfilled is almost unavoidable, it's reasonable to set at 35% the share of municipal waste sent to incineration with energy recovery. Due to the great attention given by the European Legislation to landfilling, for the lowest level of the EU Waste Hierarchy, 'Disposal', we consider the landfill rate. To prevent detrimental impacts on human health and to treat waste in line with the Waste Hierarchy principles, the EU Directive 2018/850 defined this action as the least preferable option and limited the share of landfilled municipal waste to 10% by 2035. Such a threshold is also used in our analysis. The descriptive statistics for the selected indicators are presented in Appendix A.

4.2. Step 2. Validation with panel of experts

In the previous step we have defined the structure of our problem by identifying general and specific actions undertaken by countries as criteria and sub-criteria to evaluate the waste management performance. To this extent, a number of performance indicators have been considered. As a next step, we interviewed a panel of experts to discuss our choices and to elicit their preferences over the different criteria and sub-criteria. To ensure diversity of thought, six experts with different roles and different points of view in the international waste management framework have been contacted. Specifically, we interacted with a member of the OECD Network of Economic Regulators, the scientific coordinator of Zero Waste Europe, a policy officer at the European Environmental Bureau, a waste expert at the European Environmental Agency and two policy officers at the DG Environment of the European Commission.

First, we have discussed with the experts the adequacy of the chosen criteria. There has been a common agreement with respect to the choice of including waste prevention as the first step of the waste hierarchy and determining the actions as defined in the waste hierarchy. This holistic approach is very important from a circular economy perspective, "*key to reducing the overall environmental footprints of European production and consumption, respecting planetary boundaries, and protecting human health*", and it plays a fundamental role in the upcoming reviews of the waste framework directives (European Parliament, 2021).

Second, experts have been interviewed on the sub-criteria along with the related performance indicators and thresholds as well. Legal binding targets already defined by the European legislator (such as recycling or packaging rate) have been judged the most natural choice. Regarding the area of waste prevention, there is a strong urge to develop indicators to be monitored and targets to be observed (Gözet et al., 2022). The choice of residual waste per capita has been welcomed as reflected in the European Parliament (2021)'s resolution in 2021. A few alternative potential indicators or targets have been brought to our attention, with the caveat that they are still under discussion. For example, for the circular material rate use the circular economy action plan calls for a non-binding target for the EU to double its circular material rate use in the next decade. Accordingly, a proposal might be to set a target at 25.6% by 2030, as its average level in 2020 was 12.8%. As for the energy recovery rate, a suggestion might be to bring it to 25%, given the harmful impact it displays from a climate perspective. Moreover, the increasing need to boost recycling activities might bring to a change in the currently available targets (especially as regards the packaging), but it's only under discussion to date. Similar reasoning applies to landfill rate, very likely to be revised in the mid-term waste framework and to be set on a baseline year and kg of waste per person per year in order to prevent diversion from landfilling to waste incineration and to further reduce incentives to increase the waste production (European Parliament, 2021). Although some of the discussed indicators have non-binding targets (as opposed to others already legally enforced), it is still important they are included in the analysis so to monitor the countries' transition towards the circular economy.

Third, we have asked the six experts to elicit separately their preferences over the criteria and sub-criteria, expressing which actions they consider more important and which is the intensity of this importance. Specifically, they were asked to give their judgments over the different levels of the waste hierarchy (*Prevention*, *Preparing for re-use & recycling*, *Recovery* and *Disposal*), by using the Saaty's fundamental scale in a pairwise comparison approach. In addition, they were also asked to give their judgments whenever more than one indicator is foreseen for a waste hierarchy level, that is, for *Prevention* (*Residual waste/pro capita (kg)* and *Circular material use rate*) as well as for *Preparing for re-use & recycling* (*Recycling rate of municipal waste*, *Packaging rate*, *Paper and cardboard packaging rate*, *Wooden packaging rate* and *Glass packaging rate*).

4.3. Step 3. Computation of weights

Once obtained the pairwise comparison matrices from the Experts and checked their consistency, we aggregated them all in geometric means - Expert Group (E_G) - matrices and eventually derived the priority weights. Following the test proposed by Saaty and Vargas (2007), we found that the expert group judgments exhibit small dispersion.

With respect to the judgements expressed over the different levels of the waste hierarchy (*Prevention*, *Preparing for re-use & recycling*, *Recovery* and *Disposal*), the resulting $E_G^{'}$ matrix is the following:

$$E_G^{'} = \begin{array}{l} \\ \text{Prevention} \\ \text{Preparing \& recycling} \\ \text{Recovery} \\ \text{Disposal} \end{array} \begin{array}{cccc} \text{Prevention} & \text{Preparing \& recycling} & \text{Recovery} & \text{Disposal} \\ \end{array} \left[\begin{array}{cccc} 1 & 3 & 7.83 & 9 \\ 0.33 & 1 & 6.52 & 7.61 \\ 0.13 & 0.15 & 1 & 2.50 \\ 0.11 & 0.13 & 0.40 & 1 \end{array} \right] \tag{2}$$

The maximum eigenvalue of the pairwise comparison matrix is $\lambda_{\max} = 4.1834$, the Coefficient of Inconsistency is $CI = \frac{\lambda_{\max}-4}{3} = 0.0611$ and the Inconsistency ratio is $IR = \frac{CI}{0.882} = 0.0693$, where 0.882 is the coefficient of random inconsistency, that is the average Coefficient of Inconsistency for randomly filled reciprocal matrices (see for all Franek and Kresta, 2014). Since $IR < 0.1$, the judgement matrix is consistent. The normalized eigenvector associated with $\lambda_{\max}$ determines the weights associated with the considered actions of the EU Waste Hierarchy, that is

$$\begin{array}{ccccc} & \text{Prevention} & \text{Preparing \& recycling} & \text{Recovery} & \text{Disposal} \\ \text{Weights}_{HIERARCHY} = [& 0.5811 & 0.3062 & 0.0709 & 0.0418\ ] \end{array}$$

Priority weights need to be computed not only for the actions associated with the waste hierarchy levels, but also within each level whenever more than one indicator is chosen. With respect to the judgements expressed over the different indicators selected for Prevention (*Residual waste/pro capita (kg)* and *Circular material use rate*), the resulting $E_G^{''}$ matrix is the following:

$$E_G^{''} = \begin{array}{l} \\ \text{Residual waste} \\ \text{Circular material use rate} \end{array} \begin{array}{cc} \text{Residual waste} & \text{Circular material use rate} \end{array} \left[\begin{array}{cc} 1 & 4.72 \\ 0.21 & 1 \end{array} \right] \tag{3}$$

Being a 2-by-2 matrix, the judgement matrix is consistent. The normalized eigenvector associated with $\lambda_{\max}$ determines the weights associated with the indicators selected for Prevention, that is

$$\begin{array}{ccc} & \text{Residual waste} & \text{Circular material use rate} \\ \text{Weights}_{PREVENTION} = [& 0.8251 & 0.1749\ ] \end{array}$$

With respect to the judgements expressed over the different indicators selected for Preparing for re-use & Recycling (*Recycling rate of municipal waste*, *Packaging rate*, *Paper and cardboard packaging rate*, *Wooden packaging rate* and *Glass packaging rate*), the resulting $E^{'''}$ matrix is the following:

$$E_G^{'''} = \begin{array}{l} \\ \text{Recycling} \\ \text{Packaging} \\ \text{Paper} \\ \text{Plastic} \\ \text{Wooden} \\ \text{Glass} \end{array} \begin{array}{cccccc} \text{Recycling} & \text{Packaging} & \text{Paper} & \text{Plastic} & \text{Wooden} & \text{Glass} \end{array} \left[\begin{array}{cccccc} 1.00 & 3.71 & 4.28 & 4.28 & 4.28 & 4.28 \\ 0.27 & 1.00 & 3.93 & 3.93 & 3.93 & 3.93 \\ 0.23 & 0.25 & 1.00 & 0.83 & 1.00 & 1.00 \\ 0.23 & 0.25 & 1.20 & 1.00 & 1.20 & 1.20 \\ 0.23 & 0.25 & 1.00 & 0.83 & 1.00 & 1.00 \\ 0.23 & 0.25 & 1.00 & 0.83 & 1.00 & 1.00 \end{array} \right] \tag{4}$$

The maximum eigenvalue of the pairwise comparison matrix is $\lambda_{\max} = 6.1842$, the Coefficient of Inconsistency is $CI = \frac{\lambda_{\max}-6}{5} = 0.0368$ and the Inconsistency ratio is $IR = \frac{CI}{1.25} = 0.0295$, where 1.25 is the coefficient of random inconsistency. Since $IR < 0.1$, the judgement matrix is consistent. The normalized eigenvector associated with $\lambda_{\max}$ determines the weights associated with the indicators selected for Preparing & Recycling, that is

$$\begin{array}{ccccccc} & \text{Recycling} & \text{Packaging} & \text{Paper} & \text{Plastic} & \text{Wooden} & \text{Glass} \\ \text{Weights}_{PREP\&RECYCLING} = [& 0.4369 & 0.2557 & 0.0745 & 0.0840 & 0.0745 & 0.0745\ ] \end{array}$$

Accordingly, the derived priority weights associated with the chosen indicators are the following:

$$\text{Weights} = \begin{array}{l} \text{Residual waste} \\ \text{Circular material use rate} \\ \text{Recycling} \\ \text{Packaging} \\ \text{Paper} \\ \text{Plastic} \\ \text{Wooden} \\ \text{Glass} \\ \text{Energy recovery rate} \\ \text{Landfill rate} \end{array} \left[\begin{array}{c} 0.4795 \\ 0.1016 \\ 0.1338 \\ 0.0783 \\ 0.0228 \\ 0.0257 \\ 0.0228 \\ 0.0228 \\ 0.0709 \\ 0.0418 \end{array} \right] \tag{5}$$

Before proceeding with the aggregation of the indicators (or better, their deviations from the thresholds), a further aspect needs to be discussed as we did with the panel of experts. As described in Section 3.2, the Goal Programming Synthetic Indicator adds up two types of deviations: one refers to the country's strengths $GPSI_i^S$ and the other to the country's weaknesses $GPSI_i^W$. To this extent, two possible scenarios arise.

The first one considers the same set of weights (5) for both $GPSI_i^S$ and $GPSI_i^W$, as in Blancas et al. (2010). In this case the same importance is assigned to positive and to negative deviations from the given aspiration levels. Countries whose strengths are related to the highest levels of the EU Waste Hierarchy are the best positioned with respect to those with good performance in the lowest levels. The weight system associated with the pairwise comparison matrix (2) strongly rewards countries which are on the good path towards the circular economy and overcome the linear model for waste management. In this regard, we refer to this scenario as the one with a *hierarchical circular perspective*.

The above outlined scenario is lenient with countries whose infringements are in the lower part of the EU Waste Hierarchy. In these countries, recover and disposal actions still play an overly relevant role in their waste management, resulting in linear patterns detrimental from a circular perspective. If the highest levels of the EU Waste Hierarchy and their ambitious thresholds trace the direction for further environmental improvements, the lowest levels are related to essential requirements that should have been already fulfilled. Consequently, whenever weaknesses are investigated, higher importance could be assigned to those indicators associated with the lowest levels of the Waste Hierarchy. To represent this second perspective (hereafter, the *linear treatment penalizing perspective*), a second scenario is considered. Differently from Blancas et al. (2010), for every country i, $GPSI_i^S$ and $GPSI_i^W$ are computed by using different systems of weights. In this case, deviations related to the country's strengths and deviations related to country's weaknesses have different scale of importance (for applications with different weights, see for example Aznar et al., 2011). The first one is associated with the pairwise comparison matrix (2) and it is related to the strengths of the countries, so that it gives more importance to the higher levels of the EU Waste Hierarchy. The second one is related to the weaknesses of the countries so that it gives more importance to the lower part of the Waste Hierarchy. This second pairwise comparison matrix is obtained as the transpose of the matrix (2). In this way, countries with weaknesses in the lowest level of the Waste Hierarchy are penalized with respect to the first scenario. From the discussion with the experts, this second scenario appeared to be a useful alternative measure of countries' performance and suitable to complement the previous one. It is in line with the interests of the legislator that foresees punishments for infringements in the lower parts of the waste hierarchy rather than in the upper ones.

Table 3 summarises the weights used to aggregate the deviations from the aspiration levels into a Goal Programming Synthetic Indicator under the "hierarchical circular perspective" and the "linear treatment penalizing perspective".

4.4. Step 4. Aggregation of indicators - Results

The Goal Programming Synthetic Indicator (GPSI) has been computed for the EU-28 countries to assess to which extent these countries comply with the European Union requirements in terms of waste management, and more broadly, support the transition towards a circular economy. The empirical results have been obtained applying the four steps outlined in Section 3. Here below we report first the results of the Goal Programming Synthetic Indicator obtained using the same weights both for the strengths and the weaknesses of each country (hierarchical circular perspective). Then, we present the results for the alternative aggregating measure of deviations, penalizing the countries that do not meet the set targets in the lower tiers of the Waste Hierarchy (linear treatment penalizing perspective).

The maps in Fig. 3 and Fig. 4 give an overview of the countries' performance according to the computed GPSI for the latest available year, that is 2018. Specifically, countries reporting alarming -very low- performance scores are in red, average performance scores in yellow, while encouraging -very high- performance scores in green. Table 4 and Table 5 provide more detailed information on the obtained results. Specifically, they display the total GPSI ranking, together with the partial results for the $GPSI^S$ which aggregates the strengths of a country and its counterpart $GPSI^W$ for the weaknesses. To ease the reading of strengths and weaknesses of each country, we report respectively with a positive sign the $GPSI^S$ and with a negative sign the $GPSI^W$. Accordingly, the total $GPSI$ is equal to the sum of $GPSI^S$ and $GPSI^W$, as well as to the sum of all the positive and negative components linked to each Waste Hierarchy-related sub-indicator.

Beyond the cross-sectional analysis, interesting insights might emerge investigating the performance evolution of the EU-28 countries over time. For this reason, we replicated the analysis for each year, from 2013 to 2018, and we compared the change in the countries' ranking between the two outlined scenarios. Fig. 5 shows the change of the EU-28 countries' ranking over time in the hierarchical circular perspective, while Fig. 6 in the linear treatment penalizing perspective. The GPSIs and the ranking for each year and country are presented in details in Appendix B.

Table 3
Overview of the priority weights used to aggregate the deviations from the aspiration levels into a Goal Programming Synthetic Indicator under two different perspectives.

		Hierarchical circular perspective		*Linear treatment penalizing perspective*	
Waste Hierarchy	Indicators	Weights for GPSI^S	Weights for GPSI^W	Weights for GPSI^S	Weights for GPSI^W
Prevention	Residual waste	0.4795	0.4795	0.4795	0.0335
	Circular material use rate	0.1016	0.1016	0.1016	0.0071
Preparing & recycling	Recycling	0.1338	0.1338	0.1338	0.0336
	Packaging	0.0783	0.0783	0.0783	0.0197
	Paper	0.0228	0.0228	0.0228	0.0057
	Plastic	0.0257	0.0257	0.0257	0.0065
	Wooden	0.0228	0.0228	0.0228	0.0057
	Glass	0.0228	0.0228	0.0228	0.0057
Recovery	Energy recovery rate	0.0709	0.0709	0.0709	0.3272
Disposal	Landfill rate	0.0418	0.0418	0.0418	0.5553

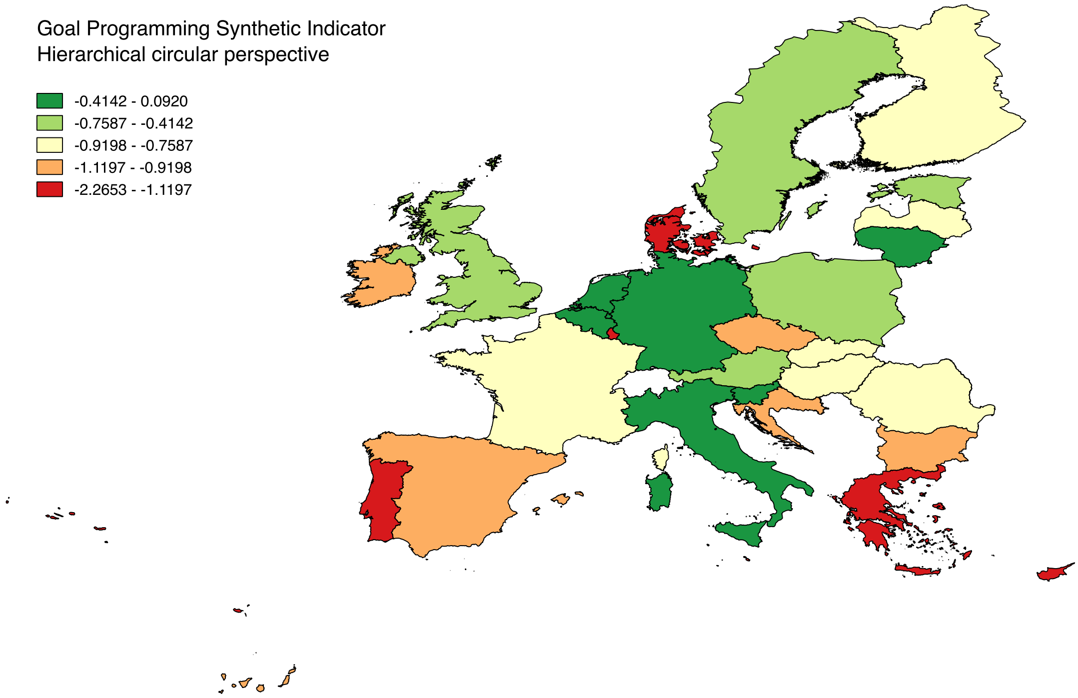

Fig. 3. Performance of the EU-28 countries in a hierarchical circular perspective (data for 2018). Countries reporting alarming -very low- performance scores are in red, average performance scores in yellow, while encouraging -very high- performance scores in dark green. *Source*: Authors' own elaboration on Eurostat data.

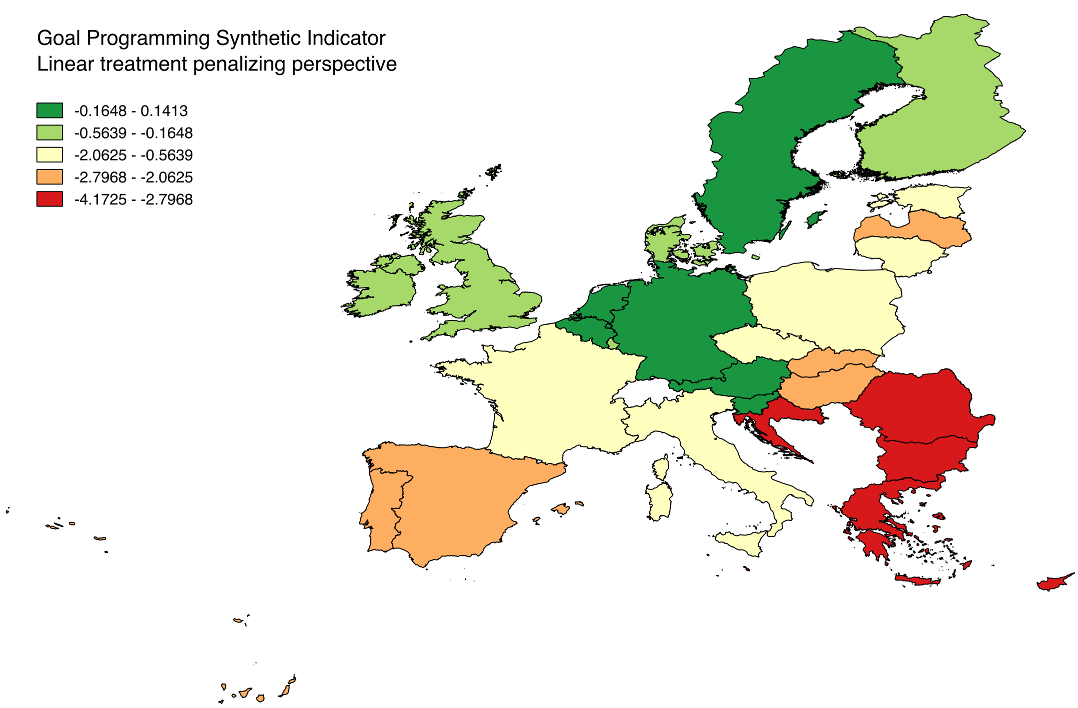

Fig. 4. Performance of the EU-28 countries in a linear treatment penalizing perspective (data for 2018). Countries reporting alarming -very low- performance scores are in red, average performance scores in yellow, while encouraging -very high- performance scores in dark green. *Source*: Authors' own elaboration on Eurostat data.

Table 4
Performance of the EU-28 countries measured with the Goal Programming Synthetic Indicator (GPSI) in a hierarchical circular perspective (data for 2018). *Source*: Authors' own elaboration on Eurostat data.

					Prevention		Re-use and recycling						Recovery	Disposal
Country	Rank	*GPSI*	$GPSI^S$	$GPSI^W$	Residual waste	Circular rate	Recycling rate	Packaging rate	Paper packaging	Plastic packaging	Wood packaging	Glass packaging	Energy rate	Landfill rate
Austria	7	−0.5079	0.0355	−0.5434	−0.4671	−0.0407	−0.0051	−0.0050	−0.0002	−0.0108	−0.0071	0.0029	−0.0073	0.0326
Belgium	2	−0.1530	0.1258	−0.2788	−0.2454	0.0150	−0.0125	0.0171	0.0028	−0.0059	0.0461	0.0071	−0.0150	0.0377
Bulgaria	18	−0.9593	0.0598	−1.0191	−0.6302	−0.0883	−0.0635	−0.0107	−0.0058	0.0020	−0.0066	0.0017	0.0562	−0.2140
Croatia	21	−1.0338	0.0731	−1.1069	−0.6611	−0.0754	−0.0774	−0.0130	0.0023	−0.0083	−0.0199	−0.0166	0.0708	−0.2352
Cyprus	27	−1.7206	0.0861	−1.8066	−1.3559	−0.0872	−0.0970	0.0002	0.0035	−0.0003	−0.0155	0.0129	0.0695	−0.2507
Czechia	20	−0.9928	0.0496	−1.0424	−0.7670	−0.0588	−0.0620	−0.0004	0.0002	0.0009	0.0114	−0.0023	0.0371	−0.1519
Denmark	24	−1.2174	0.0525	−1.2700	−1.1481	−0.0578	−0.0225	−0.0026	0.0018	−0.0110	0.0119	0.0016	−0.0280	0.0371
Estonia	11	−0.7221	0.0023	−0.7245	−0.5382	−0.0278	−0.0713	−0.0107	0.0003	−0.0081	−0.0074	0.0020	−0.0128	−0.0481
Finland	17	−0.9100	0.0519	−0.9619	−0.7924	−0.0701	−0.0395	0.0002	0.0083	−0.0112	−0.0043	0.0046	−0.0445	0.0388
France	13	−0.7798	0.0113	−0.7910	−0.6961	0.0032	−0.0332	−0.0048	0.0019	−0.0131	0.0009	0.0037	0.0015	−0.0437
Germany	3	−0.2978	0.0676	−0.3655	−0.3186	−0.0374	0.0158	−0.0017	0.0005	−0.0040	−0.0038	0.0051	0.0078	0.0384
Greece	26	−1.5660	0.0717	−1.6377	−1.1621	−0.0840	−0.0889	−0.0016	0.0039	−0.0064	−0.0073	−0.0014	0.0679	−0.2861
Hungary	12	−0.7679	0.0437	−0.8116	−0.4816	−0.0642	−0.0504	−0.0267	−0.0047	−0.0117	−0.0053	−0.0012	0.0437	−0.1658
Ireland	22	−1.0683	0.0259	−1.0942	−0.8944	−0.0931	−0.0499	−0.0068	−0.0016	−0.0112	0.0259	−0.0033	−0.0156	−0.0182
Italy	6	−0.3517	0.0585	−0.4102	−0.3292	−0.0016	−0.0227	−0.0019	−0.0013	−0.0052	0.0243	0.0008	0.0335	−0.0481
Latvia	15	−0.8253	0.0670	−0.8923	−0.5058	−0.0760	−0.0776	−0.0159	−0.0006	−0.0090	−0.0021	−0.0011	0.0670	−0.2044
Lithuania	5	−0.3295	0.0522	−0.3818	−0.2076	−0.0786	−0.0167	−0.0104	−0.0020	0.0067	−0.0047	−0.0006	0.0455	−0.0611
Luxembourg	25	−1.2457	0.0315	−1.2772	−1.1731	−0.0439	−0.0245	0.0010	−0.0013	−0.0106	0.0012	0.0054	−0.0237	0.0238
Malta	28	−2.2653	0.0709	−2.3362	−1.7631	−0.0583	−0.1115	−0.0385	−0.0092	−0.0167	−0.0228	−0.0099	0.0709	−0.3061
Netherlands	4	−0.3110	0.1375	−0.4485	−0.4238	0.0535	−0.0091	0.0091	0.0006	−0.0022	0.0325	0.0061	−0.0135	0.0359
Poland	9	−0.5916	0.0258	−0.6174	−0.3540	−0.0497	−0.0584	−0.0126	0.0009	−0.0090	−0.0007	0.0002	0.0248	−0.1329
Portugal	23	−1.1540	0.0695	−1.2235	−0.8654	−0.0904	−0.0689	−0.0139	−0.0049	−0.0099	0.0353	−0.0099	0.0341	−0.1602
Romania	16	−0.9036	0.0627	−0.9664	−0.4430	−0.0936	−0.1090	−0.0135	0.0010	−0.0056	−0.0012	−0.0050	0.0617	−0.2954
Slovakia	14	−0.8244	0.0747	−0.8991	−0.5739	−0.0749	−0.0528	−0.0038	−0.0022	−0.0017	0.0178	0.0001	0.0568	−0.1898
Slovenia	1	0.0920	0.1461	−0.0541	0.0890	−0.0481	−0.0025	0.0001	−0.0024	0.0025	0.0017	−0.0012	0.0512	0.0016
Spain	19	−0.9793	0.0782	−1.0576	−0.7620	−0.0503	−0.0562	−0.0013	−0.0034	−0.0020	0.0281	0.0027	0.0474	−0.1824
Sweden	8	−0.5467	0.0575	−0.6042	−0.4649	−0.0658	−0.0317	0.0001	−0.0021	−0.0023	0.0160	0.0024	−0.0374	0.0390
United Kingdom	10	−0.6520	0.0040	−0.6560	−0.5592	−0.0144	−0.0354	−0.0088	−0.0028	−0.0052	0.0040	−0.0030	−0.0062	−0.0209
EU-28 countries		−0.8423	0.0605	−0.9028	−0.6605	−0.0521	−0.0477	−0.0063	−0.0006	−0.0061	0.0053	0.0001	0.0230	−0.0975

Notes: To help the reader in interpreting the strengths and the weaknesses of each country, we report respectively with a positive sign the $GPSI^S$ and with a negative sign the $GPSI^W$.

Table 5
Performance of the EU-28 countries measured with the Goal Programming Synthetic Indicator (GPSI) in a linear treatment penalizing perspective (data for 2018). *Source*: Authors' own elaboration on Eurostat data.

					Prevention		Re-use and recycling						Recovery	Disposal
Country	Rank	*GPSI*	$GPSI^S$	$GPSI^W$	Residual waste	Circular rate	Recycling rate	Packaging rate	Paper packaging	Plastic packaging	Wood packaging	Glass packaging	Energy rate	Landfill rate
Austria	5	−0.0410	0.0355	−0.0764	−0.0326	−0.0028	−0.0013	−0.0013	−0.0001	−0.0027	−0.0018	0.0029	−0.0338	0.0326
Belgium	4	0.0349	0.1258	−0.0909	−0.0171	0.0150	−0.0031	0.0171	0.0028	−0.0015	0.0461	0.0071	−0.0692	0.0377
Bulgaria	23	−2.8524	0.0598	−2.9123	−0.0440	−0.0062	−0.0160	−0.0027	−0.0015	0.0020	−0.0017	0.0017	0.0562	−2.8403
Croatia	24	−3.1351	0.0731	−3.2082	−0.0462	−0.0053	−0.0194	−0.0033	0.0023	−0.0021	−0.0050	−0.0042	0.0708	−3.1228
Cyprus	25	−3.3711	0.0861	−3.4571	−0.0947	−0.0061	−0.0244	0.0002	0.0035	−0.0001	−0.0039	0.0129	0.0695	−3.3281
Czechia	17	−2.0403	0.0496	−2.0899	−0.0536	−0.0041	−0.0156	−0.0001	0.0002	0.0009	0.0114	−0.0006	0.0371	−2.0160
Denmark	7	−0.1699	0.0525	−0.2225	−0.0802	−0.0040	−0.0057	−0.0006	0.0018	−0.0028	0.0119	0.0016	−0.1292	0.0371
Estonia	14	−0.7590	0.0023	−0.7614	−0.0376	−0.0019	−0.0179	−0.0027	0.0003	−0.0020	−0.0019	0.0020	−0.0590	−0.6384
Finland	9	−0.2273	0.0519	−0.2792	−0.0553	−0.0049	−0.0099	0.0002	0.0083	−0.0028	−0.0011	0.0046	−0.2052	0.0388
France	13	−0.6309	0.0113	−0.6422	−0.0486	0.0032	−0.0083	−0.0012	0.0019	−0.0033	0.0009	0.0037	0.0015	−0.5807
Germany	3	0.0404	0.0676	−0.0272	−0.0222	−0.0026	0.0158	−0.0004	0.0005	−0.0010	−0.0010	0.0051	0.0078	0.0384
Greece	26	−3.8402	0.0717	−3.9120	−0.0811	−0.0059	−0.0223	−0.0004	0.0039	−0.0016	−0.0018	−0.0003	0.0679	−3.7985
Hungary	19	−2.2208	0.0437	−2.2644	−0.0336	−0.0045	−0.0127	−0.0067	−0.0012	−0.0029	−0.0013	−0.0003	0.0437	−2.2012
Ireland	11	−0.3750	0.0259	−0.4009	−0.0624	−0.0065	−0.0125	−0.0017	−0.0004	−0.0028	0.0259	−0.0008	−0.0718	−0.2418
Italy	12	−0.6112	0.0585	−0.6697	−0.0230	−0.0001	−0.0057	−0.0005	−0.0003	−0.0013	0.0243	0.0008	0.0335	−0.6387
Latvia	22	−2.7133	0.0670	−2.7803	−0.0353	−0.0053	−0.0195	−0.0040	−0.0001	−0.0023	−0.0005	−0.0003	0.0670	−2.7130
Lithuania	15	−0.7870	0.0522	−0.8392	−0.0145	−0.0055	−0.0042	−0.0026	−0.0005	0.0067	−0.0012	−0.0002	0.0455	−0.8106
Luxembourg	8	−0.1722	0.0315	−0.2037	−0.0819	−0.0031	−0.0062	0.0010	−0.0003	−0.0027	0.0012	0.0054	−0.1096	0.0238
Malta	28	−4.1725	0.0709	−4.2434	−0.1231	−0.0041	−0.0280	−0.0097	−0.0023	−0.0042	−0.0057	−0.0025	0.0709	−4.0638
Netherlands	2	0.0429	0.1375	−0.0946	−0.0296	0.0535	−0.0023	0.0091	0.0006	−0.0005	0.0325	0.0061	−0.0622	0.0359
Poland	16	−1.7872	0.0258	−1.8130	−0.0247	−0.0035	−0.0147	−0.0032	0.0009	−0.0023	−0.0002	0.0002	0.0248	−1.7646
Portugal	18	−2.1513	0.0695	−2.2208	−0.0604	−0.0063	−0.0173	−0.0035	−0.0012	−0.0025	0.0353	−0.0025	0.0341	−2.1271
Romania	27	−3.9296	0.0627	−3.9923	−0.0309	−0.0065	−0.0274	−0.0034	0.0010	−0.0014	−0.0003	−0.0012	0.0617	−3.9211
Slovakia	21	−2.5053	0.0747	−2.5800	−0.0401	−0.0052	−0.0133	−0.0010	−0.0006	−0.0004	0.0178	0.0001	0.0568	−2.5195
Slovenia	1	0.1413	0.1461	−0.0049	0.0890	−0.0034	−0.0006	0.0001	−0.0006	0.0025	0.0017	−0.0003	0.0512	0.0016
Spain	20	−2.4161	0.0782	−2.4943	−0.0532	−0.0035	−0.0141	−0.0003	−0.0008	−0.0005	0.0281	0.0027	0.0474	−2.4218
Sweden	6	−0.1614	0.0575	−0.2189	−0.0325	−0.0046	−0.0080	0.0001	−0.0005	−0.0006	0.0160	0.0024	−0.1728	0.0390
United Kingdom	10	−0.3552	0.0040	−0.3591	−0.0390	−0.0010	−0.0089	−0.0022	−0.0007	−0.0013	0.0040	−0.0007	−0.0284	−0.2768
EU-28 countries		−1.4702	0.0605	−1.5307	−0.0432	−0.0013	−0.0115	−0.0008	0.0006	−0.0012	0.0082	0.0016	−0.0034	−1.4193

Notes: To help the reader in interpreting the strengths and the weaknesses of each country, we report respectively with a positive sign the $GPSI^S$ and with a negative sign the $GPSI^W$. Accordingly, the total *GPSI* is equal to the sum of $GPSI^S$ and $GPSI^W$, as well as to the sum of all the positive and negative components linked to each waste hierarchy-related indicator.

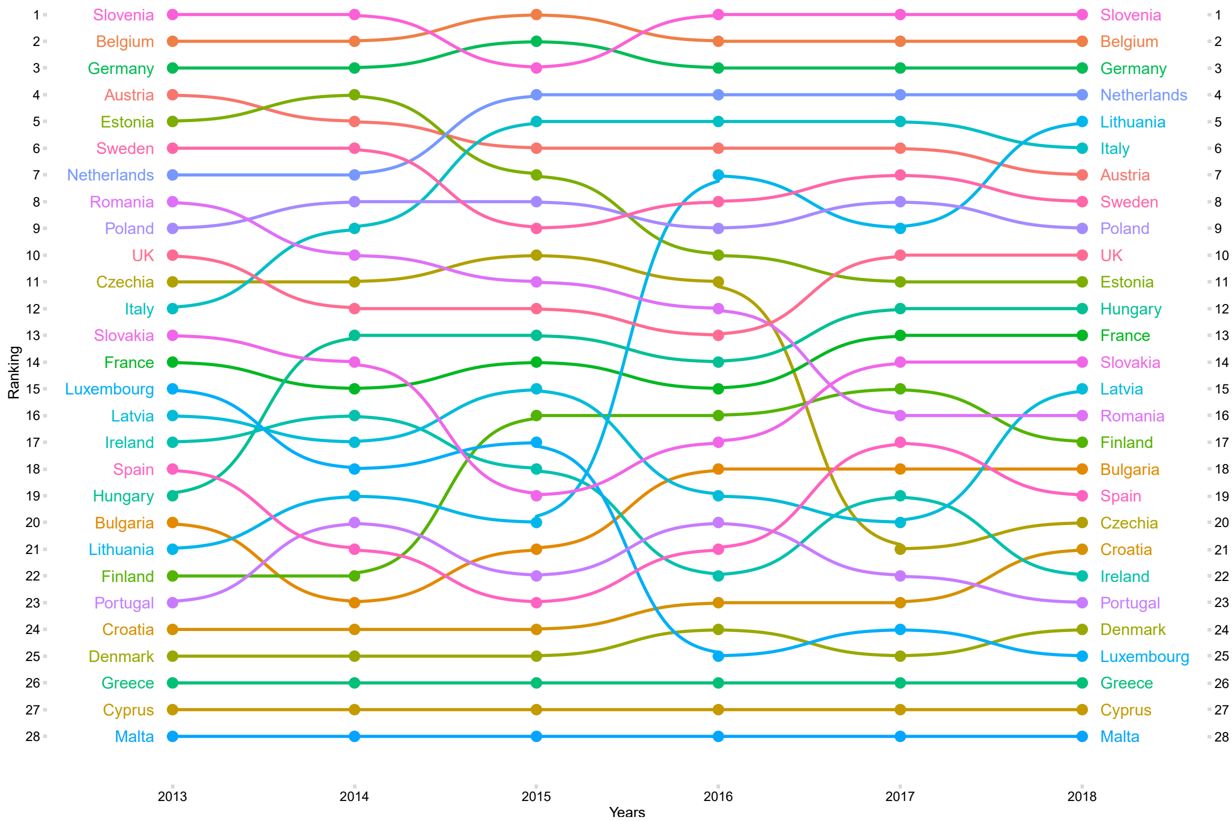

Fig. 5. Change of the EU-28 countries' ranking over time - Hierarchical circular perspective. *Source*: Authors' own elaboration on Eurostat data.

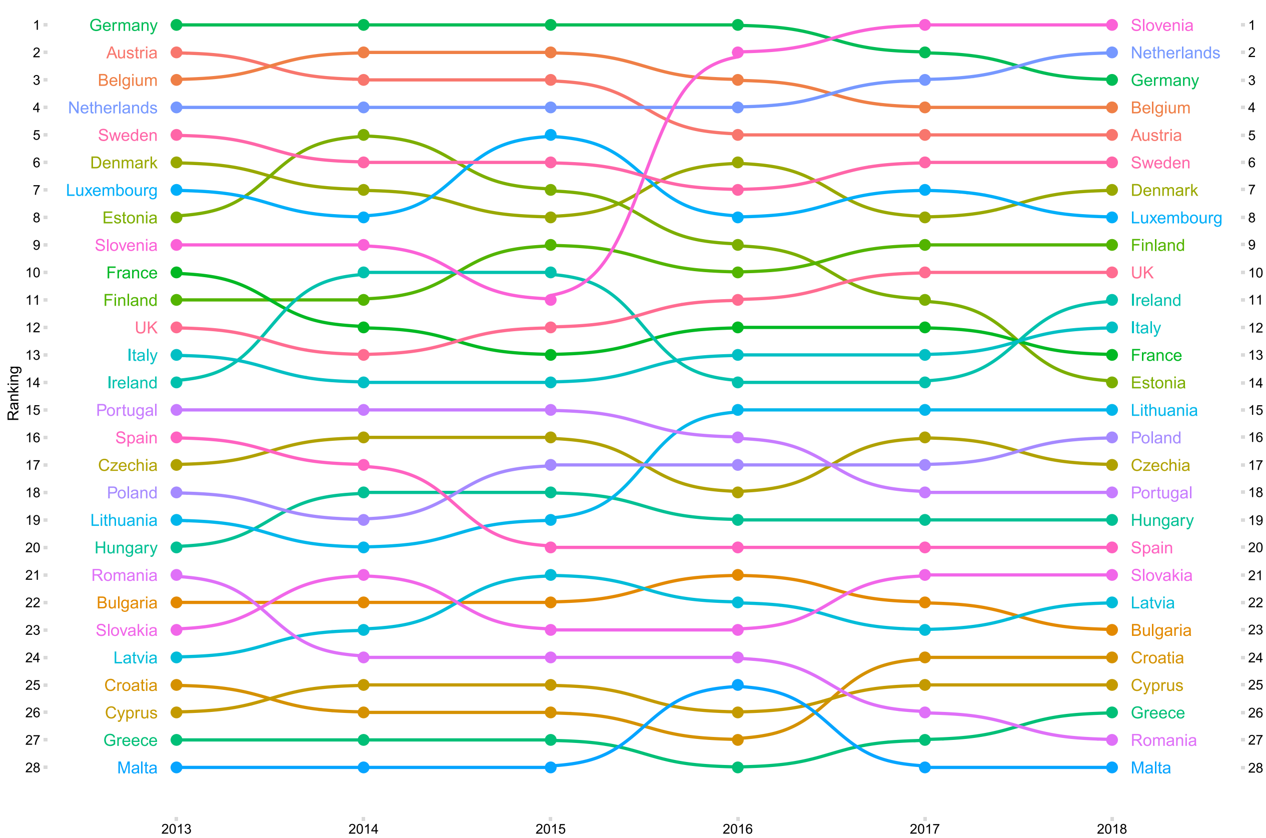

Fig. 6. Change of the EU-28 countries' ranking over time - Linear treatment penalizing perspective. *Source*: Authors' own elaboration on Eurostat data.

5. Discussion of results

5.1. On the hierarchical circular perspective

When considering the hierarchical circular perspective, we observe that Slovenia, Belgium, Germany, The Netherlands, Lithuania and Italy lead as the top performers, while Portugal, Denmark, Luxembourg, Greece, Cyprus and Malta are at the bottom of the ranking. These very low performing countries are characterised by high rates of landfilling, along with low overall recycling rate and quite low circularity rate. Moreover, they have high levels of residual waste production per capita primarily due to tourism and cannot rely on citizens' engagement, found as one of the most successful factors in waste prevention and recovery (Lee et al., 2017).

The EU-28 countries report a virtuous contribution to the GPSI only for the recycling rate of wood and glass packaging, together with the energy recovery rate. All the other negative entries suggest that on average Europe is still far from achieving the targets set by the EU policy maker and from fulfilling the requirements of the EU Waste Hierarchy. Slovenia is the only country with a positive GPSI, denoting that the areas where it has already met the targets outperform the areas where it is still recovering. Slovenia is the only country that has succeeded in meeting the Zero Waste Europe target of reducing the residual waste per capita below 120 kg. This is the result of a successful strong awareness campaigns encouraging citizens towards great levels of recovery, along with renouncing to the incinerators as a conscious strategy to reduce waste and to foster recycling (Romano et al., 2021). To this extent, Ljubljana has been declared the European Green Capital in 2016 and the first European capital to move towards zero waste (Lee et al., 2017). Indeed, there are trade-offs between existing waste treatment capacities and recycling results. Yamamoto and Kinnaman (2022) studying Japanese municipalities found that excess incineration capacity reduces recycling. Slovenia results seem to confirm that there should be a careful planning to adequately consider such trade-offs in order to fulfill expected reducing and recycling results. Belgium together with The Netherlands is the frontrunner in the recycling rate of packaging waste. These two countries together with France are the only countries that have already met the long-term objective of a circulation material use rate above 19%. Germany is the only country meeting already the recycling rate target, with a leading position in the remanufacturing activities by German enterprises in the world (Lee et al., 2017). With respect to landfill rate, only 9 out of 28 countries have met the 2030 target of no more than 10 per cent of municipal waste landfilled (Lee et al., 2017).A reduction in landfill use is frequently associated with an increase in incineration (Yamamoto and Kinnaman, 2022; OECD, 2019); thus, increasing incineration, while one expected target is reached (that of reducing landfilling) another one is at risk (that of increasing recycling) as in Denmark case (OECD, 2019). However, recent studies report conflicting results for the relationship between incineration and recycling (Kinnaman and Yamamoto, 2023). Lithuania, for example, demonstrated the ability to concurrently increase recycling and energy recovery, while significantly decrease landfill use.

When considering the change of ranking over time, we should consider that there are different marginal compliance costs among EU countries due to diverse starting points in waste hierarchy compliance. We observe that the top three performing countries identified for 2018 are the same over the years and the same applies for the three lagging countries. Few countries display interesting trends that deserve to be discussed. For example, Lithuania presents a remarkable improvement over the years. Lithuania increased its efforts for improving most of the targets for prevention and recycling: from 2013 and 2018 residual waste per capita decreased by 43% (-29% between 2015 and 2016), while the circularity rate increased by 34% (+12% between 2015 and 2016); further, recycling rate increased by 89%, with improvements in most of packaging materials. Such efforts had also effects on the landfill rate, that decreased by 61% from 2013 and 2018, with a sharp decrease between 2015 and 2016 (-45% in a year). Energy recovery was also exploited, with increases in the energy recovery rate, even if with a decrease by 32% in the last year analysed (2017/2018). On the contrary, we find for example Luxembourg, Romania, Ireland and Portugal on the opposite path. Luxembourg worsened its results mainly between 2015 and 2016. In this span of time, data showed a sharp increase (30%) of residual waste generation per capita and a decrease in the circularity rate by 28%, even if also landfilling was reduced (-38% of landfill rate). Similarly, Romania from 2016 to 2017 was penalized from a sharp increase of 20% and 16% of residual waste generation per capita and landfill rate, respectively. Ireland and Portugal data describe countries where there was not a clear strategy to follow the waste hierarchy and to increase target reaching capability. Their achievements in meeting the targets did not change significantly over time and only report some modifications, frequently reversed the following years (Portugal) or denoting progressively a deterioration (Ireland).

5.2. On the linear treatment penalizing perspective

Moving from the hierarchical to the linear penalizing perspective, there are some remarkable differences that we can spot. For example, among the top 5 performers Austria overtakes Italy, which shows only an average performance compared to the other countries. Despite the rewarding efforts in the recycling area, there is still an open challenge for Italy for the waste disposal. Similarly, Romania joins the bottom of the ranking having one of the largest rates of landfilled waste.

More in general, from the map we can observe that in this scenario a more systematic clusters of European countries emerges. In line with the evidence found in Castillo-Giménez et al. (2019), Central and Northern EU members show better performance than Mediterranean and in particular Eastern European countries, whose one of the main challenges is the landfill reduction. To this extent, Table 5 shows that the top performing countries are those reporting a positive contribution in the disposal area. However, this aspect needs to be further elaborated and policy makers should be warned. Meeting the 10% target of landfill rate might trigger some vicious practices. For example, Denmark is one of the few countries meeting the landfill target, but at the same time it reports one of the highest levels of residual waste per capita (407.36 kg in 2018) and the highest generated waste per capita (812 kg in 2018) among the European countries. Finland is also characterized by a similar situation (Romano et al., 2021). In these countries, most of the waste is sent to incineration for energy recovery. However, "achieving a target of zero municipal waste to landfill through the incineration of waste is deceptive, as the secondary residue, which can be substantial, is typically landfilled" (Lee et al., 2017). Further, incineration for energy recovery could not be considered as a circular way to treat waste also in accordance with the Article 17 of the Taxonomy Regulation that establishes a framework to facilitate sustainable investment. In this context, the EU clearly states that economic activities leading to "a significant increase in the generation, incineration or disposal of waste, with the exception of the incineration of non-recyclable hazardous waste" do harm the objective of the circular economy transition.

Moving from a hierarchical to a linear penalizing perspective does affect the evolution over time of the countries' performance. For example, the great improvement undertaken by Slovenia in the last years is quite evident. The analysis clearly captures the step change marked in 2016 when Ljubljana has been declared the European Green Capital and more generally Slovenia has succeeded in meeting the Zero Waste Europe target of reducing the residual waste, reducing both landfilling and incineration through energy recovery, encouraging reduction, re-use and recycling (Lee et al., 2017; Romano et al., 2021). As another example, we can remark the downward shift in the ranking of countries like Italy and Romania with respect to the previous scenario. However, while Italy manages to counterbalance the penalizing effect of having landfilled waste with high recycling rate of different packaging types, Romania tends to worsen over the years.

5.3. Policy implications

This comprehensive analysis highlights three main aspects. First, it shows the relevance of a holistic approach to ease and support the transition towards a Circular Economy throughout the waste management. Second, it emphasizes the importance of introducing and using adequate performance analysis able to account of waste hierarchy targets and to benchmark countries (and even municipalities' and firms' results). Third, it remarks the need to adopt clear strategies and policies to change (in most of the EU countries) existing approaches, to improve the effective adoption of the EU Waste Hierarchy so to foster the Circular Economy transition in due time. To this extent, policy makers might use the ranking to identify countries that have developed virtuous circular strategies, taking them as an example to follow. Looking at the frontrunners, lagging countries might be inspired to use a number of policy instruments, such as landfill taxes and landfill ban as imposed in The Netherlands and in Belgium, the 'Pay As You Throw' scheme and strong awareness campaigns as organized in Slovenia, buying remanufactured products as proposed in Germany, to name a few (see also Lee et al., 2017).

Nevertheless, the EU legislator and the national authorities should be aware of the triggered mechanisms when enacting any measure. It might not be sufficient to focus only on the lower tiers of the EU Waste Hierarchy, despite denoting a linear economic pattern with harmful environmental consequences. Instead, policy instruments should be promoted to reduce waste generation at source as a priority and avoid situations where countries put less effort in recycling to divert more investments to meet requirements in the lower tiers of the Waste Hierarchy, e.g. disposal, as for example the above-mentioned case of Denmark and Finland.

6. Conclusions

In the last two decades, European countries have been increasingly challenged to move towards a Circular Economy within the waste management framework. The main objective is not only to reduce the amount of waste generation, but also to prevent it in the first place. The Waste Hierarchy proposed by the EU legislator embeds this goal and identifies a number of actions that countries are supposed to undertake, where 'Prevention' is at top as the most preferred option and 'Disposal' is at the bottom as the least preferred one.

In this paper we suggest an innovative composite indicator combining the Analytic Hierarchy Process (AHP) with the Goal Programming Synthetic Indicator (GPSI) methodology to evaluate the EU-28 countries' compliance with the EU Waste Hierarchy and with several related targets that European countries are supposed to meet in the near future. The AHP smoothly enables us to integrate the EU legislator rationale behind the EU Waste Hierarchy and provides an exogenous system of weights to aggregate the deviations from the targets in an overall GPSI. To the best of our knowledge, from a methodological perspective, this is the first time combining AHP and GPSI. This approach provides a performance evaluation tool more refined than the ones already existing using the two techniques separately and where the DMs are highly taken into account. From the AHP, we can include weights obtained eliciting preferences of the DMs. From the GPSI, we can rank the units under evaluation using information on positive and negative deviations from thresholds validated by the DMs. With this approach, the DMs are involved both when eliciting the preferences and when validating the thresholds.

Taking into account the peculiarities of our application, two different systems of weights are proposed. In the first one, strengths and weaknesses in the waste management of each country are treated on an equal footing, in a *hierarchical circular perspective*. In the second system, we focus our attention on the European legislation worries about countries bad performance in the lowest levels of the Hierarchy. In this case, indicators associated with negative deviations assume weights which are reversed with respect to the weights foreseen for the positive deviations. To this extent, countries with weaknesses in the lower tiers of the hierarchy are more penalised, outlying a *linear treatment penalizing perspective* and detrimental to the Circular Economy transition.

The main results show that EU countries have implemented the EU requirements in different ways and responded with different strategies. For the period under analysis 2013–2018, we observe a group of frontrunners, namely Slovenia, Netherlands, Belgium and Germany, and a group of lagging countries, Cyprus, Croatia, Greece and Malta, regardless of the weights we consider to construct the GPSI. On the contrary, the comparison of the two scenarios helps to identify countries that have particularly succeeded or worsened over time. Only very few countries have already met the targets and on average the EU-28 countries display a virtuous pattern only in some recycling activities. The overall GPSI is increasing over time, even if lagging countries have not managed to catch up with the leading ones.

This study remarks the importance of having harmonised and detailed data to provide accurate analysis and sound recommendations to policy makers. Eurostat, in collaboration with the EU countries, has made noticeable efforts to gather data to enable cross-country comparisons and accordingly to identify effective strategies. Future research should encourage data collection at sub-national level and replicate the analysis at a lower level to increase the monitoring and provide more refined benchmarking exercises. As highlighted by Romano et al. (2021), case studies at local level could help to identify in depth the actions realized to change the linear path or to improve the results such as in Ljubljana, Porto or Helsinki. Moreover, in view of the constantly evolving European legislation, further research might consider including new upcoming different indicators, as discussed with the panel of experts. This is the case for example of landfill measurement; our analysis is based on the current legislation, where the share of landfilled municipal waste is set to 10% by 2035. Nevertheless, many stakeholders (European Parliament Members among others) are pushing for the introduction of a landfill target in kg of waste per person per year. Similarly, the indicator on kg per capita of the produced municipal waste would be an advisable measure for "Prevention" even though there is no unanimous consensus about the suitable threshold to be used. Finally the proposed methodology could be also used to investigate to which extent European countries' fulfill the requirements for other waste categories, such as the industrial waste management and the hazardous waste management.

CRediT authorship contribution statement

Giovanna D'Inverno: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Laura Carosi:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Giulia Romano:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Descriptive statistics

Table A.1
Descriptive statistics for the selected indicators.

Waste hierarchy	Indicator		Mean	Std. Dev.	Min	Max	Observations	Targets
Prevention	Residual waste/per capita (kg)	overall	287.04	94.47	97.73	691.39	N = 168	⩽120 kg
		between		92.95	119.88	547.81	n = 28	
		within		23.31	210.05	430.62	T = 6	
Prevention	Circular material use rate	overall	8.79	6.24	1.40	29.70	N = 168	⩾19%
		between		6.27	1.77	27.78	n = 28	
		within		0.94	5.02	13.32	T = 6	
Re-use and recycling	Recycling rate of municipal waste	overall	35.85	14.75	7.40	67.20	N = 168	⩾60%
		between		14.37	10.00	66.25	n = 28	
		within		4.16	21.11	51.30	T = 6	
Re-use and recycling	Packaging rate	overall	63.50	9.05	35.60	85.30	N = 168	⩾70%
		between		8.62	37.87	82.08	n = 28	
		within		3.13	45.85	72.42	T = 6	
Re-use and recycling	Paper and cardboard packaging rate	overall	82.67	11.09	48.40	116.10	N = 168	⩾85%
		between		10.20	53.57	109.52	n = 28	
		within		4.69	58.57	96.77	T = 6	
Re-use and recycling	Plastic packaging rate	overall	41.58	12.34	19.20	81.70	N = 168	⩾55%
		between		11.60	24.33	66.20	n = 28	
		within		4.67	23.35	57.08	T = 6	
Re-use and recycling	Wooden packaging rate	overall	38.45	24.84	0.00	131.50	N = 168	⩾30%
		between		23.29	1.92	97.72	n = 28	
		within		9.52	10.92	72.23	T = 6	
Re-use and recycling	Glass packaging rate	overall	71.65	19.17	11.60	119.80	N = 168	⩾75%
		between		18.05	15.18	98.05	n = 28	
		within		7.15	48.33	97.82	T = 6	
Recovery	Energy recovery rate	overall	22.50	18.26	0.00	58.53	N = 168	⩽35%
		between		18.21	0.07	51.76	n = 28	
		within		3.43	7.04	33.86	T = 6	
Disposal	Landfill rate	overall	37.36	29.45	0.44	105.26	N = 168	⩽10%
		between		29.35	0.64	85.34	n = 28	
		within		5.64	18.23	57.29	T = 6	

Notes: EU-28 countries data for 2013 to 2018. Data available at https://ec.europa.eu/eurostat/web/waste/data/database. *Source*: Authors' own elaboration on Eurostat data, last accessed April 2021.

Appendix B. Additional tables

Table B.1
Change of EU 28 countries' ranking over time with respect to the Goal Programming Synthetic Indicator (GPSI) - Hierarchical circular perspective.

	2013		2014		2015		2016		2017		2018	
Country	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI
Austria	4	−0.4773	5	−0.4888	6	−0.4855	6	−0.4727	6	−0.4917	7	−0.5079
Belgium	2	−0.2696	2	−0.2286	1	−0.2103	2	−0.2225	2	−0.1612	2	−0.1530
Bulgaria	20	−1.0642	23	−1.1269	21	−1.0006	18	−0.9272	18	−0.9420	18	−0.9593
Croatia	24	−1.3160	24	−1.2236	24	−1.2139	23	−1.1853	23	−1.1291	21	−1.0338
Cyprus	27	−1.9745	27	−1.8227	27	−1.8750	27	−1.8650	27	−1.9111	27	−1.7206
Czechia	11	−0.7553	11	−0.7151	10	−0.6510	11	−0.6372	21	−0.9631	20	−0.9928
Denmark	25	−1.4592	25	−1.3688	25	−1.3069	24	−1.2681	25	−1.3077	24	−1.2174
Estonia	5	−0.5075	4	−0.4006	7	−0.4987	10	−0.5796	11	−0.6848	11	−0.7221
Finland	22	−1.0738	22	−1.0410	16	−0.8796	16	−0.8350	15	−0.8775	17	−0.9100
France	14	−0.9337	15	−0.8993	14	−0.8608	15	−0.8326	13	−0.8092	13	−0.7798
Germany	3	−0.3843	3	−0.3577	2	−0.3324	3	−0.3250	3	−0.3222	3	−0.2978
Greece	26	−1.6450	26	−1.6335	26	−1.6137	26	−1.5913	26	−1.5659	26	−1.5660
Hungary	19	−0.9965	13	−0.8839	13	−0.8573	14	−0.8104	12	−0.7979	12	−0.7679
Ireland	17	−0.9814	16	−0.9017	18	−0.9051	22	−0.9805	19	−0.9440	22	−1.0683
Italy	12	−0.7876	9	−0.6287	5	−0.4830	5	−0.4385	5	−0.3902	6	−0.3517
Latvia	16	−0.9694	17	−0.9367	15	−0.8697	19	−0.9321	20	−0.9594	15	−0.8253
Lithuania	21	−1.0682	19	−1.0071	20	−0.9769	7	−0.4782	9	−0.6025	5	−0.3295
Luxembourg	15	−0.9394	18	−0.9466	17	−0.9001	25	−1.2991	24	−1.2470	25	−1.2457
Malta	28	−2.0259	28	−2.0650	28	−2.8922	28	−1.9409	28	−2.1752	28	−2.2653

(*continued on next page*)

Table B.1 (*continued*)

	2013		2014		2015		2016		2017		2018	
Country	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI
Netherlands	7	−0.5491	7	−0.5237	4	−0.4798	4	−0.4128	4	−0.3433	4	−0.3110
Poland	9	−0.7128	8	−0.6067	8	−0.5471	9	−0.5554	8	−0.5672	9	−0.5916
Portugal	23	−1.1005	20	−1.0153	22	−1.0047	20	−0.9749	22	−1.0857	23	−1.1540
Romania	8	−0.6429	10	−0.6761	11	−0.6641	12	−0.6875	16	−0.8879	16	−0.9036
Slovakia	13	−0.8910	14	−0.8922	19	−0.9368	17	−0.9011	14	−0.8754	14	−0.8244
Slovenia	1	−0.0761	1	−0.0277	3	−0.3337	1	−0.0652	1	0.0742	1	0.0920
Spain	18	−0.9874	21	−1.0177	23	−1.0566	21	−0.9753	17	−0.9391	19	−0.9793
Sweden	6	−0.5302	6	−0.5138	9	−0.5668	8	−0.5352	7	−0.5622	8	−0.5467
United Kingdom	10	−0.7330	12	−0.7225	12	−0.7045	13	−0.7100	10	−0.6729	10	−0.6520

Source: Authors' own elaboration on Eurostat data.

Table B.2
Change of EU 28 countries' ranking over time with respect to the Goal Programming Synthetic Indicator (GPSI) - Linear treatment penalizing perspective.

	2013		2014		2015		2016		2017		2018	
Country	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI	Rank	GPSI
Austria	2	−0.0114	3	−0.0251	3	−0.0352	5	−0.0302	5	−0.0400	5	−0.0410
Belgium	3	−0.0127	2	−0.0069	2	−0.0083	3	−0.0056	4	0.0240	4	0.0349
Bulgaria	22	−3.2713	22	−3.3083	22	−3.1247	21	−3.0103	22	−2.8727	23	−2.8524
Croatia	25	−4.0370	26	−3.9186	26	−3.8974	27	−3.7268	24	−3.4887	24	−3.1351
Cyprus	26	−4.0479	25	−3.8215	25	−3.8426	26	−3.7268	25	−3.8695	25	−3.3711
Czechia	17	−2.5858	16	−2.5448	16	−2.3426	18	−2.1952	16	−1.9840	17	−2.0403
Denmark	6	−0.2379	7	−0.2203	8	−0.1757	6	−0.1465	8	−0.1911	7	−0.1699
Estonia	8	−0.4271	5	−0.1193	7	−0.1681	9	−0.2045	11	−0.6470	14	−0.7590
Finland	11	−0.9880	11	−0.6332	9	−0.2692	10	−0.2165	9	−0.2447	9	−0.2273
France	10	−0.9480	12	−0.8884	13	−0.8261	12	−0.7486	12	−0.6895	13	−0.6309
Germany	1	0.0434	1	0.0496	1	0.0501	1	0.0467	2	0.0401	3	0.0404
Greece	27	−4.1483	27	−4.1686	27	−4.1505	28	−4.0559	27	−3.9314	26	−3.8402
Hungary	20	−3.0548	18	−2.6546	18	−2.4492	19	−2.2874	19	−2.1611	19	−2.2208
Ireland	14	−1.5624	10	−0.6120	10	−0.6137	14	−0.9061	14	−0.7309	11	−0.3750
Italy	13	−1.5056	14	−1.1911	14	−0.8844	13	−0.7861	13	−0.7229	12	−0.6112
Latvia	24	−3.5579	23	−3.3867	21	−2.8813	22	−3.0175	23	−3.0524	22	−2.7133
Lithuania	19	−2.9322	20	−2.7369	19	−2.4678	15	−1.0766	15	−1.2602	15	−0.7870
Luxembourg	7	−0.3373	8	−0.3365	5	−0.1407	8	−0.1745	7	−0.1747	8	−0.1722
Malta	28	−4.2361	28	−4.2480	28	−5.4377	25	−3.6779	28	−3.9620	28	−4.1725
Netherlands	4	−0.0797	4	−0.0706	4	−0.0488	4	−0.0105	3	0.0318	2	0.0429
Poland	18	−2.8960	19	−2.6778	17	−2.4438	17	−1.9886	17	−1.9961	16	−1.7872
Portugal	15	−2.2596	15	−2.1422	15	−2.0393	16	−1.9195	18	−2.0483	18	−2.1513
Romania	21	−3.2707	24	−3.4238	24	−3.4220	24	−3.2908	26	−3.9305	27	−3.9296
Slovakia	23	−3.3491	21	−3.1714	23	−3.2749	23	−3.0738	21	−2.8039	21	−2.5053
Slovenia	9	−0.8059	9	−0.6100	11	−0.6918	2	0.0340	1	0.1184	1	0.1413
Spain	16	−2.5377	17	−2.6494	20	−2.6334	20	−2.4448	20	−2.2787	20	−2.4161
Sweden	5	−0.1314	6	−0.1432	6	−0.1613	7	−0.1511	6	−0.1525	6	−0.1614
United Kingdom	12	−1.3566	13	−1.0371	12	−0.7664	11	−0.5944	10	−0.4483	10	−0.3552

Source: Authors' own elaboration on Eurostat data.

References

Aczél, J., Saaty, T.L., 1983. Procedures for synthesizing ratio judgements. J. Math. Psychol. 27 (1), 93–102.

Amenta, P., Lucadamo, A., Marcarelli, G., 2021. On the choice of weights for aggregating judgments in non-negotiable AHP group decision making. Eur. J. Oper. Res. 288 (1), 294–301.

Argoubi, M., Jammeli, H., Masri, H., 2020. The intellectual structure of the waste management field. Ann. Oper. Res. 1–22.

Aznar, J., Guijarro, F., Moreno-Jiménez, J.M., 2011. Mixed valuation methods: a combined AHP-GP procedure for individual and group multicriteria agricultural valuation. Ann. Oper. Res. 190 (1), 221–238.

Basso, A., Funari, S., 2020. A three-system approach that integrates DEA, BSC, and AHP for museum evaluation. Decisions Econ. Finan. 43 (2), 413–441.

Bianchi, M., Cordella, M., 2023. Does circular economy mitigate the extraction of natural resources? empirical evidence based on analysis of 28 european economies over the past decade. Ecol. Econ. 203, 107607.

Blancas, F.J., González, M., Lozano-Oyola, M., Pérez, F., 2010. The assessment of sustainable tourism: Application to Spanish coastal destinations. Ecological indicators 10 (2), 484–492.

Blengini, G., Mathieux, F., Mancini, L., Nyberg, M., Viegas, H., 2019. Recovery of critical and other raw materials from mining waste and landfills. European Commission, JRC Science for Policy Report.

Castillo-Giménez, J., Montañés, A., Picazo-Tadeo, A.J., 2019. Performance and convergence in municipal waste treatment in the European Union. Waste Manage. 85, 222–231.

Charnes, A., Cooper, W.W., 1961. Management Models and Industrial Applications of Linear Programming. Wiley, New York.

Chen, T.Y., 2002. Measuring firm performance with DEA and prior information in taiwan's banks. Appl. Econ. Letters 9 (3), 201–204.

Chioatto, E., Sospiro, P., 2022. Transition from waste management to circular economy: the European Union roadmap. Environ. Dev. Sustain. 1–28.

Condamine P (2020) Can the european union support waste prevention without a proper legislation? Tech. rep., Zero Waste Europe, URL https://zerowasteeurope.eu/wp-content/uploads/2020/06/zero_waste_europe_policy-briefing_waste_prevention_framework_en.pdf.

Despotis, D., 2005. Measuring human development via Data Envelopment Analysis: the case of Asia and the Pacific. Omega 33 (5), 385–390.

Domenech, T., Bahn-Walkowiak, B., 2019. Transition towards a resource efficient circular economy in europe: policy lessons from the eu and the member states. Ecol. Econ. 155, 7–19.

Egüez, A., 2021. Compliance with the EU waste hierarchy: A matter of stringency, enforcement, and time. J. Environ. Manage. 280, 111672.

Einhäupl, P., Van Acker, K., Peremans, H., Van Passel, S., 2021. The conceptualization of societal impacts of landfill mining–a system dynamics approach. J. Cleaner Prod. 296, 126351.

European Commission (2015) Closing the loop—an EU action plan for the circular economy. Communication no. 614. URL https://ec.europa.eu/environment/circular-economy/.

European Commission (2017) The role of waste-to-energy in the circular economy, Communication no. 34. URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017DC0034&from=en.

European Parliament (2021) European Parliament resolution of 10 february 2021 on the New Circular Economy Action Plan. https://www.europarl.europa.eu/doceo/document/TA-9-2021-0040_EN.html.
Eurostat (2019) Municipal waste statistics https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics.
Franek, J., Kresta, A., 2014. Judgment scales and consistency measure in ahp. Procedia Econ. Finance 12, 164–173.
Gözet B, Wilts H, Manshoven S, Bakas I (2022) Progress towards preventing waste in europe: the case of textile waste prevention.
Ho, W., Ma, X., 2018. The state-of-the-art integrations and applications of the analytic hierarchy process. Eur. J. Oper. Res. 267 (2), 399–414.
Ishizaka, A., Nemery, P., 2013. Multi-criteria decision analysis: methods and software. John Wiley & Sons.
Kinnaman, T.C., Yamamoto, M., 2023. Has incineration replaced recycling? Evidence from OECD countries. Sustainability 15 (4), 3234.
Lansink, A., 2018. Challenging changes–connecting waste hierarchy and circular economy. Waste Manage. Res. 36 (10), 872–872.
Lee, P., Sims, E., Bertham, O., Symington, H., Bell, N., Pfaltzgraff, L., Sjögren, P., Wilts, C. H., O'Brien, M., 2017. Towards a circular economy: waste management in the EU. Study. Sci. Technol. Options Assess.
Llanquileo-Melgarejo, P., Molinos-Senante, M., Romano, G., Carosi, L., 2021. Evaluation of the impact of separative collection and recycling of municipal solid waste on performance: An empirical application for chile. Sustainability 13 (4), 2022.
Lozano-Oyola, M., Blancas, F.J., González, M., Caballero, R., 2012. Sustainable tourism indicators as planning tools in cultural destinations. Ecol. Ind. 18, 659–675.
Luzzati, T., Gucciardi, G., 2015. A non-simplistic approach to composite indicators and rankings: an illustration by comparing the sustainability of the eu countries. Ecological Economics 113, 25–38.
Machiels, L., Bernardo, E., Jones, P.T., et al., 2019. Enhanced landfill mining, the missing link to a circular economy 2.0? preface to the special issue on resource recovery through enhanced landfill mining. In: Detritus Volume 08-December 2019-Special Issue on New-MINE project, vol 8, Cisa Publisher-Eurowaste Srl, pp 1–4.
Marin, G., Nicolli, F., Zoboli, R., 2018. Catching-up in waste management. Evidence from the EU. J. Environ. Plann. Manage. 61 (11), 1861–1882.
Minoja, M., Romano, G., 2021. Managing intellectual capital for sustainability: Evidence from a re-municipalized, publicly owned waste management firm. J. Cleaner Prod. 279, 123213.
Molinos-Senante, M., Marques, R.C., Perez, F., Gómez, T., Sala-Garrido, R., Caballero, R., 2016. Assessing the sustainability of water companies: A synthetic indicator approach. Ecol. Ind. 61, 577–587.
Mu, E., Cooper, O., Peasley, M., 2020. Best practices in Analytic Network Process studies. Expert Syst. Appl. 159, 113536.
OECD (2019) OECD Environmental Performance Reviews: Denmark 2019. DOI https://doi.org/https://doi.org/10.1787/1eeec492-en, URL https://www.oecd-ilibrary.org/content/publication/1eeec492-en.
Pakkar, M.S., 2014. Using data envelopment analysis and analytic hierarchy process to construct composite indicators. J. Appl. Operational Res. 6 (3), 174–187.
Pakkar, M.S., 2015. An integrated approach based on DEA and AHP. CMS 12 (1), 153–169.
Pehme, K.M., Orupõld, K., Kuusemets, V., Tamm, O., Jani, Y., Tamm, T., Kriipsalu, M., 2020. Field study on the efficiency of a methane degradation layer composed of fine fraction soil from landfill mining. Sustainability 12 (15), 6209.
Pérez, F., Molinos-Senante, M., Gómez, T., Caballero, R., Sala-Garrido, R., 2018. Dynamic goal programming synthetic indicator: An application for water companies sustainability assessment. Urban Water J. 15 (6), 592–600.
Pires, A., Martinho, G., 2019. Waste hierarchy index for circular economy in waste management. Waste Manage. 95, 298–305.
Rogge, N., De Jaeger, S., Lavigne, C., 2017. Waste performance of NUTS 2-regions in the eu: A conditional directional distance benefit-of-the-doubt model. Ecol. Econ. 139, 19–32.
Romano, G., Molinos-Senante, M., 2020. Factors affecting eco-efficiency of municipal waste services in tuscan municipalities: An empirical investigation of different management models. Waste Manage. 105, 384–394.
Romano, G., Marciano, C., Fiorelli, M.S., 2021. Best practices in urban solid waste management: Ownership, governance, and drivers of performance in a zero waste framework. Emerald Publishing, Bingley, UK.
Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15 (3), 234–281.
Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48 (1), 9–26.
Saaty, T.L., 2003. Decision-making with the AHP: Why is the principal eigenvector necessary. Eur. J. Operational Res. 145 (1), 85–91.
Saaty, T.L., Vargas, L.G., 2007. Dispersion of group judgments. Math. Computer Modell. 46 (7–8), 918–925.
Schaltegger, S., Sturm, A., 1989. Ecology induced management decision support. starting points for instrument formation. In: WWZ-Discussion Paper No. 8914, University of Basel (WWZ) Basel.
Schilkowski, C., Shukla, M., Choudhary, S., 2020. Quantifying the circularity of regional industrial waste across multi-channel enterprises. Ann. Oper. Res. 290 (1), 385–408.
Tavana, M., Soltanifar, M., Santos-Arteaga, F.J., 2021. Analytical hierarchy process: revolution and evolution. Ann. Oper. Res. 1–29.
Vaidya, O.S., Kumar, S., 2006. Analytic hierarchy process: An overview of applications. Eur. J. Oper. Res. 169 (1), 1–29.
Van Ewijk, S., Stegemann, J., 2016. Limitations of the waste hierarchy for achieving absolute reductions in material throughput. J. Cleaner Prod. 132, 122–128.
Wu, P., Ma, J., Guo, X., 2022. Efficiency evaluation and influencing factors analysis of fiscal and taxation policies: A method combining DEA-AHP and CD function. Ann. Oper. Res. 309 (1), 325–345.
Yamamoto, M., Kinnaman, T.C., 2022. Is incineration repressing recycling? J. Environ. Econ. Manage. 111, 102593.
Yu, S., Liu, J., Li, L., 2020. Evaluating provincial eco-efficiency in china: an improved network data envelopment analysis model with undesirable output. Environ. Sci. Pollution Res. 27 (7), 6886–6903.
Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., Tukker, A., 2022. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in europe. Sci. Total Environ. 803, 149892.