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Assessing the circularity performance in a European cross-country comparison

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ABSTRACT

Reuse and recycling are two of the most important strategies involved in the practical implementation of the circular economy (CE). Even if several indices have been defined to quantify the performance of waste management, none of them has integrated a mix of waste streams such as waste from electrical and electronic equipment, end-of-life vehicles, and municipal solid waste. The present paper proposes a new Waste Circularity Index (WCI) generated by a weighted average, with weights established through pairwise comparison using the analytic hierarchy process methodology. Nine indices (three for each waste stream) are combined, and three measurement logics are adopted. Results show that the 28 European Member States (MSs) can be clustered into six groups, with a reference to the European average. Denmark emerges as the best performer within the 2014–2018 timeframe. In addition, there are also contradicting results about certain waste streams in western MSs.

1. Introduction

The main goal of Circular Economy (CE) is to better use natural resources through reuse, recycling and recovery schemes, by minimising the energetic, health and environmental impact of extraction and processing (Chiappetta Jabbour et al., 2019; Lombardi et al., 2021). To this end, waste management policies have begun to shift from traditional (landfill-based) scenarios towards innovative (renewable energy-based and recycled materials-based) ones (Islam et al., 2020). Accordingly, organisations have changed their business models (Perey et al., 2018) to develop circular waste management systems, incentivise the circular flow of resources (Cobo et al., 2018) and improve the sustainability of products and processes (Luo et al., 2021). Academics have already proposed several strategies to improve national waste management policies (Du and Li, 2020; Fan and Fang, 2020). However, none of these studies considered the three most important waste streams of the last decade together, like Waste from Electrical and Electronic Equipment (WEEE), (Ismail and Hanafiah, 2020), End-of-Life Vehicles (ELVs) (D'Adamo et al., 2020b) and Municipal Solid Waste (MSW) (Srivastava et al., 2020). To this aim, the development of a waste index capable of measuring waste management performance within these three streams (e.g. recording the value of secondary raw materials (Zaman and Lehmann, 2013)) would be interesting. This measure could be coupled with the need to provide comprehensive analysis on the sustainability and circularity of waste recovery through quantitative analysis based on economic and environmental aspects (D'Adamo et al., 2021), but also on the technological approach (Sassanelli et al., 2021). Indeed, some authors have highlighted the key role that technological sustainability plays in this transition (Vacchi et al., 2021). Further efforts need to be made to better monitor the relationship between CE models and the social component (García-Muiña et al., 2021; Mies and Gold, 2021).

However, both the lack of data and the difficulty of comparing several countries' progress towards achieving SDGs in terms of the three most important waste streams previously presented (González Del Campo et al., 2020; Qin et al., 2021) counteracts its feasibility (Stefanović et al., 2016). Similarly, any rankings should be interpreted and could show that the positive performance of some countries is linked to an abnormal waste flow. Thus, multi-criteria analysis, combining complexity with simplicity, can also highlight the particularities that exist in these rankings. On this basis, the present research aimed at answering to the following research question: How can waste management performance be compared and ranked across countries?

The final aim of this paper is to define an easy way to compare both

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Nomenclature

ACR+	Association of Cities and Regions for sustainable Resource management
AHP	Analytic Hierarchy Process
c	Component of column vector
cap	Capita
CE	Circular Economy
CR	Consistency ratio
CV	Column Vector
D	Down than European average
ELV	End-of-Life Vehicle
EoL	End of Life
EU	European Union
FEAD	Federation for Waste Management and Environmental Services
GDP	Gross Domestic Product
GDP PPS	GDP Purchasing Power Standards
IntV	Intermediate value
λ_{max}	Highest eigenvalue
MaxV	Maximum value
MinV	Minimum value
MS	Member States
MSW	Municipal Solid Waste
n	Number of factors
per	Percentage
r	Component of row vector
RI	Random inconsistency
RW	Row vector
SDG	Sustainable Development Goal
U	Up than European average
WCI	Waste Circularity Index
WEEE	Waste from Electrical and Electronic Equipment

different waste streams and different Member States (MSs) performances in order to support the development of alternative monitoring systems able to assist policymakers in identifying adequate revisions of their environmental policies.

The paper is organised as follows. Section 2 presents a brief literature review about existing strategies proposed by academics to improve national waste management policies. Section 3 describes the data (with reference to the years 2014–2018) and the methodology. Section 4 proposes an MSs ranking in terms of the Waste Circularity Index (WCI). Section 5 presents some concluding remarks.

2. Literature review

Zero-waste programs and policies have been developed and applied since many years in different regions around the world. Some relevant examples are: 1) the European Green New Deal (and related Circular Economy Action Plan), 2) the Chinese New Era Green Development Report (and related report of the 19th National Congress of the Communist Party of China) and 3) Japan's Sound Material-Cycle Society Plan.

During the last decades, academics have proposed several strategies to improve national waste management policies, like multivariate ordinal logistic regression models (Evans et al., 2015) or proposing global comparisons of recycling modes (Liu et al., 2018; Wang et al., 2018). Some of them underlined the importance of monitoring to detect and appraise changes in environmental, social and economic dimensions. Some others focused about smallholder projects and adopted five different methodologies (e.g. two remote sensing and three field measurement approaches) (Wells et al., 2017). Others defined more efficient and cost-effective procedures (Marchi et al., 2017). In general terms, all of them emphasised as monitoring indices should be selected by a range of stakeholders/experts, to ensure a heterogeneous perspective (incorporating a variety of, e.g., preferences, strategies and information) and produce a realistic evaluation of public policies (Kanwal et al., 2021; Zlamparet et al., 2017). Some of them referred to radar charts (Doyen et al., 2019), others focused on different measurement approaches of Sustainable Development Goals (SDGs) (Haigh et al., 2021; Miola and Schiltz, 2019; Omri, 2020), others considered evolutional economics approaches (Monasterolo et al., 2019; Zeng and Li, 2021), others focused on recycling rates (Sander et al., 2017; Wang et al., 2019), recyclability performances (Kanwal et al., 2021; Villalba Méndez et al., 2002; Zaman and Lehmann, 2013) and recycling potentials (Dahlbo et al., 2018; Gu et al., 2018; Pindar and Dhawan, 2021). However, none of these studies considered together Waste from Electrical and Electronic Equipment (WEEE), End-of-Life Vehicles (ELVs) and Municipal Solid Waste (MSW).

One answer to this issue could be identified in the lack of available (and updated) data from official data sources, like evidenced by (Stefanović et al., 2016). However, an Analytic Hierarchy Process (AHP) methodology could be useful to increase the consistency and reliability of data (Sánchez-Garrido et al., 2021). There are several ways in which AHP may be applied. On the one hand, it can be used to define a composite index for measuring and comparing MSW management among European MSs (Castillo-Giménez et al., 2019). On the other hand, it can also be used to measure the sustainability of MSs in terms of WEEE, ELVs and MSW (Cucchiella et al., 2017).

In 2018, Europe launched the Circular Economy Action Plan (European Commission, 2018) to support the reuse, recycling and recovery of materials (Table A1). Since then, CE assessment methods have been widely described in the literature (Sassanelli et al., 2019), but there is still a stated need to compare progresses towards achieving SDGs in terms of waste management (Zorpas, 2020). The topic of the SDGs has become increasingly central to the debate even among academics (Calabrese et al., 2021; Settembre-Blundo et al., 2021).

In addition, the literature review focused on how multi-criteria analyses were applied to specifically assess how the three pillars of sustainability were investigated. These works identified specific criteria for each pillar and best alternatives in terms of process/strategy: MSW (Feyzi et al., 2019); ELV (Yang et al., 2019) and WEEE (Guarnieri et al., 2020). Within these works, multi-criteria analysis was adopted to measure the impact of technologies for a specific End of Life (EoL) option (Khan and Kabir, 2020). However, a desirable future direction towards which all sustainability analyses could tend was the one considering a separate life cycle analysis to investigate each relevant dimension (Kouloumpis and Azapagic, 2018). A common point of all these studies is that multi-criteria analysis can compare alternatives, whatever is the number of criteria considered.

3. Methods

The AHP methodology supports complex decision-making in situations where multiple (conflicting) goals can be evaluated differently, depending on the expertise of the selected decision-makers. It integrates information about the performance of each alternative (scoring criteria) and a subjective evaluation of the relevance of certain criteria (weighting factor) (D'Adamo et al., 2020a; Zhang et al., 2018). Within the present research, AHP was applied to propose a new WCI measuring waste management performance with respect to three selected waste streams. This WCI was a dimensionless index (calculated for each European MSs), generated by the multiplication of a row vector ($RV_{(MS)}$) –

representing a scoring criterion – and a column vector (CV) – representing a weighting factor.

$$WCI_{(MS)} = RV_{(MS)} * CV * 100 \quad (1)$$

Given the number of European Union (EU) MSs, 28[1] alternatives were compared, across three phases (section 3.1–3.3).

3.1. Definition of indices

First, in order to define all WCIs, data were gathered from Eurostat and used as input to define the mix of waste streams for assessment (see RQ). However, some important aspects (e.g. the illegal collection and trade of waste, illegal dumping, legal import/export and informal waste picking) were not accounted for in the official waste statistics (UNECE – United Nations Economic Commission for Europe, 2017), and this comprised a limitation of the study. Despite this limitation, Eurostat provided useful data on the waste management performance of several MSs and it should be considered a reliable source of information for further evaluations (Castillo-Giménez et al., 2019).

$$CV = \left[cWEEE_{per}\ cWEEE_{cap} cWEEE_{gdp}\ cELV_{per} cELV_{cap}\ cELV_{gdp}\ cMSW_{per} cMSW_{cap}\ cMSW_{gdp}\right]^{T} \quad (2)$$

Considering the most common, valuable and harmful categories of waste (Cucchiella et al., 2017), WEEE, ELVs and MSW were selected. The three waste categories were considered in terms of reused and recycled for WEEE, ELV and recycled for MSW according to the available Eurostat data. For each, three measurement criteria were proposed, differing from those already defined by specific EU directives (i.e., kg per capita for WEEE; percentages for ELVs and MSW). These new criteria related to not only environmental, but also social (e.g., population) and economic aspects (e.g., Gross Domestic Product Purchasing Power Standards (GDP PPS)). As shown in section 2, specific criteria associated with the three sustainability pillars were proposed for individual waste categories, while no criteria were proposed to evaluate simultaneously the three waste categories examined in this work. Here, these categories were compared under nine criteria sharing the same numerators, although there is no independence between these indices. This choice has been considered as appropriate for the following reasons: i) the literature proposed in section 2 showed that the goodness of a multicriteria analysis does not depends on the number of criteria analyzed; ii) the three variants allowed to expand the dimension measured according to different waste Directives and (through a panel of experts) it was assessed whether this was appropriate or not; iii) the idea of including the three sustainability pillars points to a future approach although it has the limitation that the indices do not measure these dimensions directly and any associated uncertainty or limitations with the lack of independence. Subsequently, nine indices were identified from the combination of the three waste streams with the three measurement criteria (Fig. 1). Finally, the $WCI_{(MS)}$ index was obtained as the product of a nine-digit row vector and a nine-digit column vector (Eq. (1)).

3.2. Definition of weighting factors

The definition of the weights associated with the indices was determined through AHP. It provides an optimal solution, considering different aspects of a decision and reducing computational effort from a large to a few number of factors (Pophali et al., 2011). Although AHP is not a new method, it is still widely used (Achillas et al., 2013). The only limitation of the methodology is that it does not derive objective weights using linear programming (e.g., discrete element analysis) (Laso et al., 2018). According to a decision-makers' pairwise comparison of all criteria, AHP elaborates a weight for each. The higher the weight, the more important the criterion (Awasthi et al., 2018a, 2018b).

In the present study, the choice of nine indices was not random, but dependent on the dimensions of the AHP comparison matrix considered – typically constituted by seven plus/minus two elements (Emrouznejad and Marra, 2017). The column vector (CV) was comprised of nine rows, corresponding to the number of indices. Each cell of the CV represented the weight of a specific index. For example, $cWEEE_{per}$ was the element of the CV measuring the weight of the $WEEE_{per}$ index.

The success of AHP depends on the user's knowledge in the specific area. To this end, the present study involved a survey of experts from several MSs with extensive experience in waste management. Three categories of experts were selected: i) academics, ii) politicians and iii) managers. Academics were chosen by the guest editors of special issues, who had recently (within the past two years) edited on waste management topics. Politicians were selected during a workshop held in Brussels in 2019 by the Association of Cities and Regions for sustainable Resource management (ACR+). Managers were selected from a list of members of the European Federation for Waste Management and Environmental Services (FEAD). An email invitation to participate in the survey (Ladu et al., 2020) was sent to the forty experts generating twenty positive responses. All experts had at least ten years' experience in waste management (Table A2). The panel consisted of 12 men and 8 women.

Twenty individual interviews were conducted under the form of Skype video calls. This number of experts is considered suitable for a robust multicriteria analysis in the field of sustainability (Subramoniam et al., 2013). In addition, this analysis is more complete when considering different categories of stakeholders (D'Adamo et al., 2020a).

The aim of the survey was to determine the weight of the nine indexes. It was initially explained to respondents the purpose of the work, the methodology used, and the maintenance of privacy. Next, the proposed questions in Table A3 were shared. This approach allowed as to make them understand the relevance of making pairwise comparisons between criteria as to perceive the experts' know-how and proposals. Finally, it was shown how to insert the assessments in the Excel file, pointing out that their consistency would be checked automatically when all the comparisons were filled in. The expert was free to fill the file in our presence or not.

Each interview lasted, on average, one hour and allowed to comprehend the main characteristics of the new WCI. Once the logic of the selected criteria was defined, the need to couple them through a set of weights was highlighted. Specifically, each interviewee was asked to provide a priority scale for the pairwise comparisons, with the knowledge that a normalising approach would be adopted. AHP weights were calculated on the basis of a judgement scale ranging from 1 to 9 (Table A4 - (Saaty, 2008)). These pairwise comparisons were performed for all measurement criteria. Subsequently, considering the numerical rating ranges, a normalising approach was adopted. The assessment of the nine indices was normalised using the Belton and Gear[2] procedure

[1] The Eurostat data refer to the years 2014–2016, when the UK was still in the EU.

[2] Belton & Gear proposed a normalisation in which the priorities of the alternatives were measured by the maximum value instead of their sum.

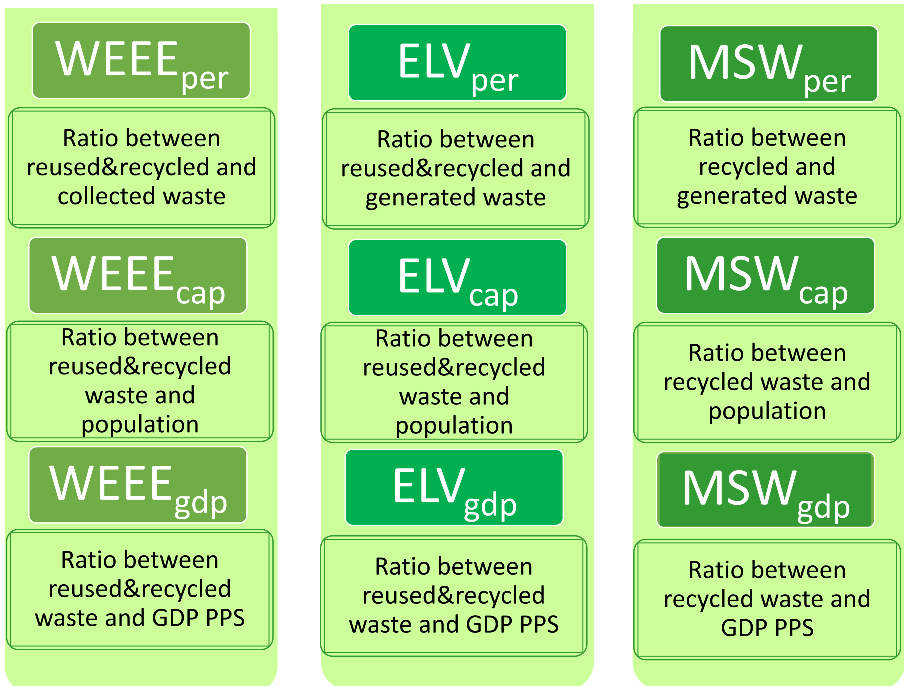

Fig. 1. Definition of indices chosen in accordance with the literature and their availability on Eurostat. The three categories (WEEE, ELV and MSW) were proposed as a function of an environmental (reused & recycled), social (population) and economic (GDP PPS) variable.

(Antonopoulos et al., 2014). Subsequently, the related geometric mean of the 20 respondents was evaluated (Subramoniam et al., 2013). The final step involved the calculation of a consistency ratio (CR), measuring the consistency of a pairwise comparison matrix (Diaz-Sarachaga et al., 2017; Giray Resat and Unsal, 2019). When the CR was lower than 0.10 (or 10%), judgements were considered trustworthy and transitivity granting, and the calculation was deemed valuable (Saaty, 2008).

$$CR = CI/RI \quad (3)$$

$$CI = (\lambda_{max} - n)/(n-1) \quad (4)$$

CI = consistency index; RI = random inconsistency (in which RI = 1.45 for $n = 9$) (Saaty, 2008); λ_{max} = highest eigenvalue (inner product of the row vector containing column sums and the Eigen vector matrix); and n = number of factors.

3.3. Definition of scoring criteria

The third step involved the construction of row vectors to evaluate each MS. RV_{MS} (row vector) was comprised of nine columns, equal to the number of indices. Each cell of the matrix represented the value of a specific index. For example, $rWEEE_{per}$ was the element of the row vector measuring the value of the $WEEE_{per}$ index.

$$RV_{(MS)} = \left[rWEEE_{per}\ rWEEE_{cap}\ rWEEE_{gdp}\ rELV_{per}\ rELV_{cap}\ rELV_{gdp}\ rMSW_{per}\ rMSW_{cap}\ rMSW_{gdp}\right] \quad (5)$$

The impact of input data uncertainty on several environmental assessment models has already been examined in the literature (Beekhuizen et al., 2014). Specifically, when data lacks homogeneity, the results can be unreliable. To this end, all of the proposed information was collected from Eurostat (Eurostat, 2021; 2019), with 2018 representing the most recent year under examination (Table A5). The analysis was then extended to examine the four prior years (2014, 2015, 2016 and 2017), to facilitate the definition of trends.[3] To construct the elements of the row vector, nine parameters were chosen from the database. Tables A6–A16 report 883 values, equivalent to approximately 92% of the data required for the analysis. When data were absent, the value of a certain parameter was maintained as constant to the nearest year (Castillo-Giménez et al., 2019; Cucchiella et al., 2017).

4. Results

Once indices, weights and measurement criteria were defined, calculation was performed. The following section reports the WCI data, which were obtained by multiplying historical values of waste reuse and recycling (from Eurostat) and selected weights (from expert judgements).

4.1. Calculation of weighting factors

Interviewees' pairwise comparisons were collected (Tables B1–B20) and normalised, according to Section 2.2. In the following example, Interviewee #1 is considered as the reference item (Table B1). Starting with the sum of the $WEEE_{cap}$ column (7.2) and considering the related value (equal to 2; see the first row and second column of the matrix $WEEE_{per}$ vs. $WEEE_{cap}$), normalisation was performed (Eq. C1). Subsequently, the weight of a specific index of the waste mix (e.g. $WEEE_{per}$) was calculated as the ratio between the sum of the $WEEE_{per}$ row and the

[3] 2018 was the latest year available on Eurostat when this research was conducted

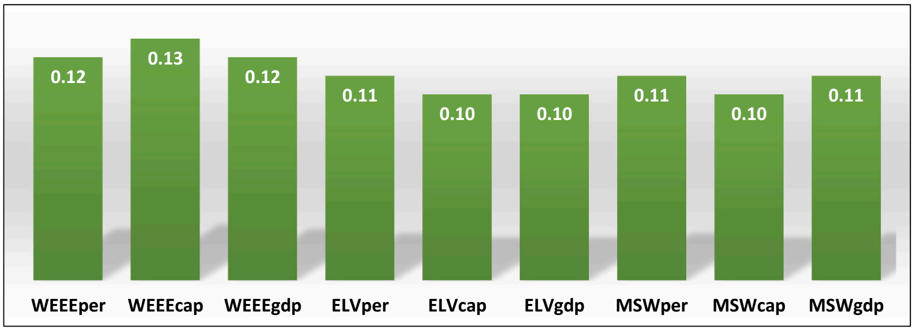

Fig. 2. The distribution of weights among the nine indices. The results show that the experts did not propose significant differences between these weights. The WEEE category has a higher incidence than MSW and ELV.

number of elements in the matrix (Eq. C2). In the present case, the resulting value was 17%. Repeating this operation for all remaining indices, the normalised column vector was obtained (Eq. C3), corresponding to the final column of Table B21. The same procedure was repeated for all interviewees. The resulting weights of the nine indices are reported in Table B22. For example, the final column of Table B21 represents the first row of Table B22. For confidentiality reasons, numbers linked to each respondent in Tables A2 and B22 are not specified.

Finally, starting from the weights obtained from the 20 respondents, the geometric mean was used to calculate the normalised column vector (Table B23 – Fig. 2). For example, by multiplying the weights attributed to the $WEEE_{per}$ index, a product equal to $1.9*10^{-19}$ was obtained; the 20th root of this value was 0.12 (Eq. C4). Alternatively, the arithmetic mean (Eq. C5) could have also been used (Kułakowski, 2015), but this would not have presented any substantial divergence (i.e. a difference of 0.002). The two averages are equal if and only if every number in the list is the same.

The aggregation of the 20 geometric means obtained from the surveyed experts produced one of the two matrices used to calculate the WCI (see Eq. (1)). The normalised CV reported in Table B23 was the same for all MSs. This approach is consistent with that proposed in the literature (Cucchiella et al., 2017). The final step in defining the scoring criteria was the evaluation of CR. First, λ_{max} represented the inner product of the last row of Table B1 and the last column of Table B21 (Eq. C6) according to Resat and Unsal (2019). Using this last value, CI was calculated (Eq. C7). Considering RI equal to 1.45 (see Section 3.2), CR was identified (Eq. C8). Before aggregating responses, the CR value was verified to be smaller than 0.10 for all 20 interviewees. Indeed, interviewees' CRs ranged from 0.081–0.098; consequently, all pairwise comparison matrices were consistent.

The AHP assessment showed that the WEEE indices had a higher weight (36.9%) than both the ELVs (32.3%) and the MSW (31.8%) indices (see Fig. 2). Six respondents identified $WEEE_{cap}$ as the most significant index, but three interviews weighted $WEEE_{per}$, $WEEE_{eco}$, ELV_{eco} and MSW_{eco} highest and another respondent weighted ELV_{cap} and MSW_{per} highest (see Table B22).

A further finding was that interviewees considered the nine criteria (rather than three) as appropriate. A slight preference has been given to the units of measurement indicated by the waste Directives ($WEEE_{cap}$, ELV_{per} and MSW_{per}), but their weight was only slightly more important than the other dimensions. In fact, interviewees believed that the $WEEE_{cap}$ index had the greatest impact on the WCI, at 12.5%, followed by $WEEE_{gdp}$ (12.3%) and $WEEE_{per}$ (12.0%). The difference in weight between several indices was not of noteworthy magnitude: for example, 2.5% between $WEEE_{cap}$ and the final index (ELV_{cap}). Thus, further research might consider an alternative scenario with an equal distribution of weights to compare different results.

However, it is possible to state that the pairwise comparison allowed to obtain a distribution of weights different from the standard one, in which all weights have equal relevance. It is equally appropriate to highlight the correctness of having considered the three different units of measurement for the three categories of waste considered. Generally, this approach can be replicated in other contexts, but it is worth highlighting how important it is to have a greater number of stakeholders in order to grasp the different nuances of thought on such a delicate issue as the green and circular transition.

4.2. Calculation of scoring criteria

Given the different scale of values presented by the indices, RV normalisation was required. In this process, 1 and 0 were assigned to the best and worst performance, respectively (Cucchiella et al., 2017). On the one hand, the indices clearly identified a positive relation. On the other hand, when the increase in the numerator exceeded the increase in the denominator (e.g. with respect to population or GDP PPS), a positive action towards the environment was evidenced. Starting from the input data (see Table A5), maximum (MaxV) and minimum (MinV) values were identified. Subsequently, one of the 26 remaining MSs with an intermediate value (IntV) was considered. $RV_{(MS)}$ values were obtained as follows: i) 1 was linked to MaxV; ii) 0 was linked to MinV and iii) finally a value ranging from 0 to 1 was obtained as (IntV-MinV)/(MaxV-MinV).

For example, considering $WEEE_{cap}$ in 2014, Sweden had a MaxV of 12.6 kg (reuse/recycled waste per capita), while Romania had a MinV of 1.4 kg. Spain presented an intermediate value of 3.1 kg (equal to 0.15 when normalised). The analysis was conducted for all three years: 2018 (Table B24), 2017 (Table B25), 2016 (Table B26), 2015 (Table B27) and 2014 (Table B28).

The scoring criteria analysis underlined that Germany had the highest performance for MSW_{per}, MSW_{cap} and MSW_{gdp} in four of the five years examined, while Slovenia led in 2015. Sweden consistently presented the best performance for $WEEE_{cap}$. In addition, it was first for ELV_{cap} in the period 2014–2016 and Ireland assumed this position in the following two years. Another country that excelled in several indices was Bulgaria: for ELV_{gdp} throughout the period examined and for $WEEE_{gdp}$ for 2014–2015 period. With regard to this last index, Croatia led in the following three years. Malta showed the best performance for $WEEE_{per}$ in 2014–2016 period. An opposite situation occurred in the following years for this country, while Croatia led $WEEE_{per}$ in 2017–2018. Finally, the maximum value for ELV_{per} was attributed to a different MS in each year (Slovakia, Poland, Greece, Croatia and again Greece, respectively).

From another perspective, Romania demonstrated the worst performance for MSW_{per}, MSW_{cap}, $WEEE_{cap}$ and $WEEE_{gdp}$ during the entire 2014–2018 period, as well as for MSW_{gdp} in 2015–2018. The worst performance was also verified for other countries, including Malta (ELV_{per}), Hungary (ELV_{cap}) and Luxembourg (ELV_{gdp}).

The analysis of values through Eurostat confers a criterion of objectivity and this provides solidity to this phase of the work. This work aims first to propose a synthetic index to collect the different information associated with waste management. This step is a fundamental requirement, since only by comparing countries will it be possible to highlight strengths and weaknesses. It also seems important to highlight how it is appropriate to consider not only one year but a wider period. Along this path of research, it will be necessary to consider recent data that will be provided from year to year in order to verify whether the trend of individual criteria and that of the WCI will be confirmed.

4.3. WCI in Europe

The WCI was derived from the product of the two vectors. The weights of all indices are presented in Fig. 2 and their values for each MS (in 2018) are proposed in Table B24. The average value of the 28 MSs (EU 28) was obtained as follows:

$$\begin{aligned} \mathrm{WCI}_{\mathrm{EU\ 28}}(\text{year 2018}) = {} & (0.54^*0.12 + 0.59^*0.13 + 0.42^*0.12 + 0.74^*0.11 \\ & + 0.34^*0.10 + 0.37^*0.10 + 0.53^*0.11 + 0.45^*0.10 \\ & + 0.54^*0.11 = 50.6 \end{aligned} \tag{5}$$

The same calculation was repeated for the four prior years (see Tables B25-B28), with the WCI value calculated as follows:

$$\begin{aligned} \mathrm{WCI}_{\mathrm{EU\ 28}}(\text{year 2017}) = {} & (0.49^*0.12 + 0.58^*0.13 + 0.44^*0.12 + 0.75^*0.11 \\ & + 0.33^*0.10 + 0.31^*0.10 + 0.53^*0.11 + 0.44^*0.10 \\ & + 0.52^*0.11 = 49.1 \end{aligned} \tag{6}$$

$$\begin{aligned} \mathrm{WCI}_{\mathrm{EU\ 28}}(\text{year 2016}) = {} & (0.42^*0.12 + 0.49^*0.13 + 0.40^*0.12 + 0.76^*0.11 \\ & + 0.49^*0.10 + 0.41^*0.10 + 0.46^*0.11 + 0.44^*0.10 \\ & + 0.52^*0.11 = 48.6 \end{aligned} \tag{7}$$

$$\begin{aligned} \mathrm{WCI}_{\mathrm{EU\ 28}}(\text{year 2015}) = {} & (0.37^*0.12 + 0.44^*0.13 + 0.28^*0.12 + 0.84^*0.11 \\ & + 0.47^*0.10 + 0.41^*0.10 + 0.43^*0.11 + 0.43^*0.10 \\ & + 0.50^*0.11 = 45.8 \end{aligned} \tag{8}$$

$$\begin{aligned} \mathrm{WCI}_{\mathrm{EU\ 28}}(\text{year 2014}) = {} & (0.31^*0.12 + 0.38^*0.13 + 0.38^*0.12 + 0.82^*0.11 \\ & + 0.48^*0.10 + 0.43^*0.10 + 0.45^*0.11 + 0.42^*0.10 \\ & + 0.52^*0.11 = 46.1 \end{aligned} \tag{9}$$

The results of these calculations can be briefly summarised as follows. First, the WCI was calculated for the 28 MSs during the years 2014–2018 and split into three components (i.e. WEEE, ELV, MSW) (Fig. 3). Second, the WCI was calculated for each MS in each year (see Fig. 4 and D1-D4). Third, MSs were clustered into two blocks: i) higher than the EU 28 mean and ii) lower than the EU 28 mean. Finally, WCI values were compared across all years; for example, the results of each MS and the EU 28 mean were compared between 2018 and 2014 (Fig. 5).

The reference level adopted in this research was the EU 28 mean, equal to 50.6 in 2018 (+1.5 relative to 2017 and + 4.5 than 2014). Considering the distribution of waste streams, maximum value was linked to ELVs (17.5; −0.6 relative to 2015), followed by WEEE (16.1; +2.7 relative to 2015) and MSW (15.0; +0.7 relative to 2015). The final contribution of ELVs was higher than that of WEEE, even though this category of waste had a lower weight (see Table B23). Regarding the percentage (e.g. per capita and per GDP PPS) of the parameters measured, all weights were equal to 33%.

EU28 significantly increased the contribution of reused and recycled e-waste from 2.85 to 3.95 million in 2014–2018 with an increase of 2.2% in the last two years examined. In terms of WCI, there were also increases because there was a decrease in the maximum baseline decreasing in 2018 compared to 2014 for the WEEE_{per} and WEEE_{cap} components. In addition, it is worth highlighting that the growth of collected waste was higher in 2018–2017 compared to reused and recycled waste, as there was a reduction in WEEE_{per} from 83.5% to 82.5%. Instead, the WEEE_{cap} increased from 7.6 to 7.7 kg per capita because the population increase was lower and equal to 0.2%, while the WEEE_{gdp} increased from 251 to 248 kg per million GDP PPS because the GDP PPS increased by 3.3%.

EU28 had also increases in terms of MSW recycled going from 67.9 to 75.1 million in 2014–2018 with a 1.1% increase in the last two years examined. In terms of WCI, there was a mirror performance to that seen for e-waste as there was a reduction in the maximum reference value in 2018 compared to 2014 for all three components. Moreover, in the period 2018–2017 there was an increase in MSWcap from 145 to 146 kg per capita while for MSWgdp a reduction from 4815 to 4711 kg per million GDP PPS. Instead, there was a positive but very minimal increase relative to MSWper from 29.5% to 29.75% measured against waste generated.

Moreover, the analysis of the last waste stream (ELV) needs to be explained because unlike the previous two, it marked a reduction in terms of WCI. This figure should be read in light of the increase of the maximum reference value. It was in fact positive the increase in terms of ELV reused and recycled that went from 5.4 to 5.9 million in the period 2014–2018 with an increase of 17.3% in the last two years examined. Thus, the increases in ELV_{cap} from 9.8 to 11.5 kg per capita and ELV_{gdp} from 325 to 369 kg per million GDP PPS were explained. In contrast, ELV_{per} decreased from 87.9% to 87.3% as waste generated increased by 18.1%.

Thirteen MSs had a value greater than the European average in 2018. Throughout the entire reference timeframe (2014–2018), Denmark (first in 2018) and Bulgaria (first in 2017) occupied the first three positions. Furthermore, Sweden was first from 2014 to 2016, Germany third in

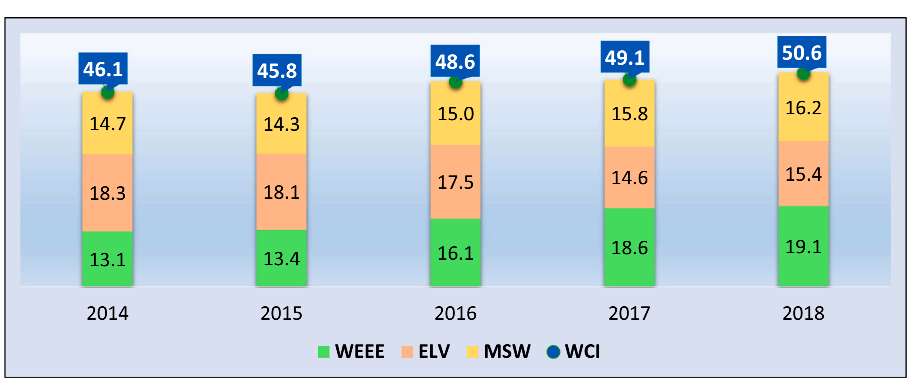

Fig. 3. WCI for all MSs during 2014–2018. Results show an increase in 2018 with improvement in all three waste categories (WEEE, ELV and MSW).

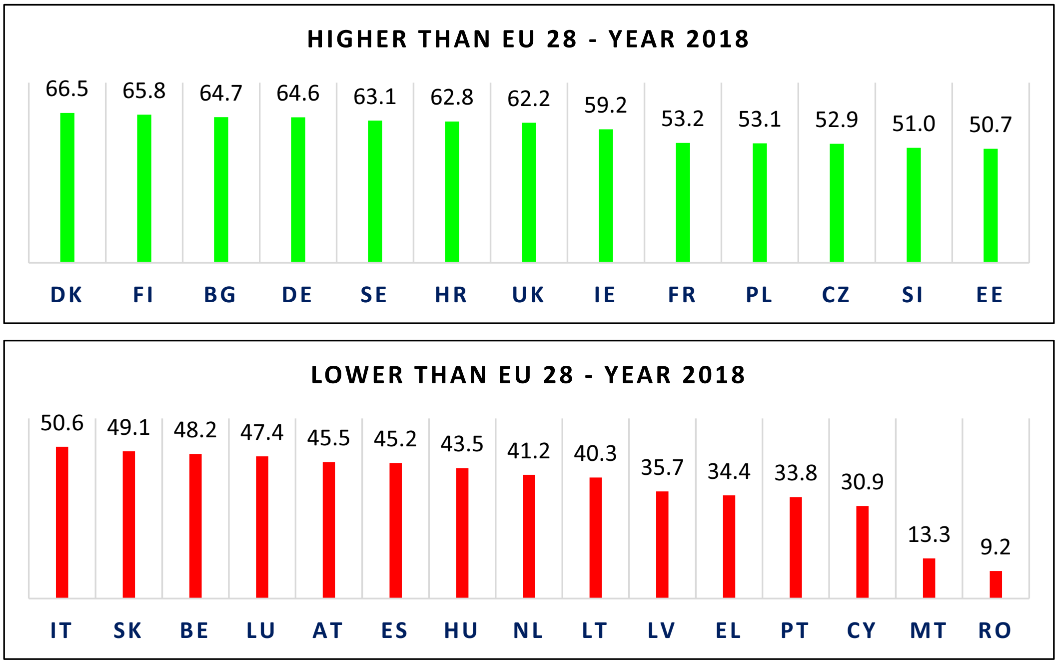

Fig. 4. WCI for all MSs in 2018. Thirteen countries have a larger WCI than the European average value of 50.6. Denmark leads the ranking, followed by Finland and Bulgaria. Italy is slightly lower than EU28.

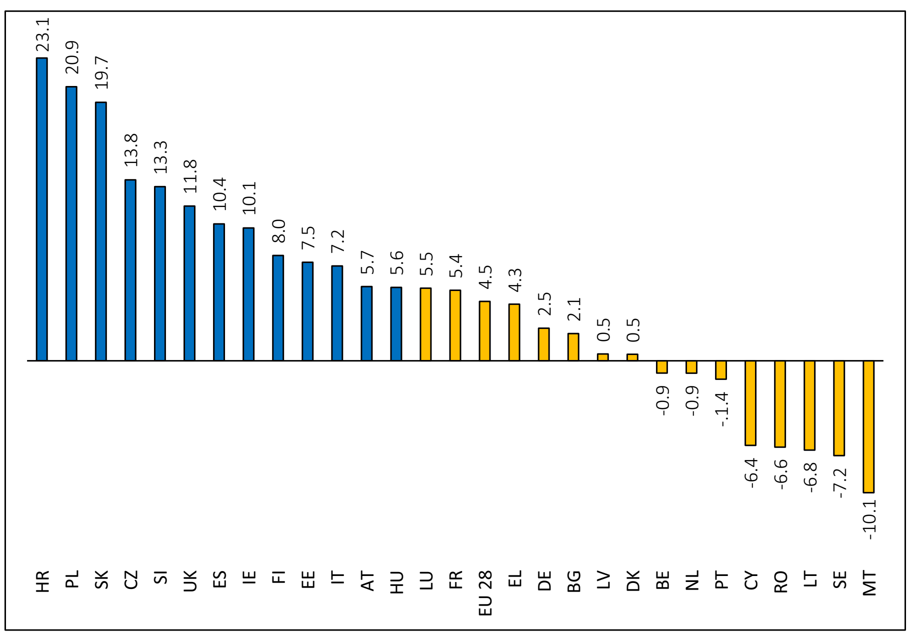

Fig. 5. WCI Δ change, 2018–2014. The results show significant changes in WCI between the various European countries, ranging from +23.1 in Croatia to −10.1 in Malta.

2017, and Finland second in 2018. These five countries always presented a WCI value greater than the EU28 mean along with three other countries (the United Kingdom, Ireland and France). In addition, other countries were consistently above the average value: Slovenia since 2015, Croatia and Czechia since 2016. Poland and Estonia rounded out the list, while Italy, albeit slightly, was below the European mean. Croatia presented a significant increase in the WCI over the 2014–2018 period, followed by Poland and Slovakia.

Reduction in the WCI did not necessarily reflect less reuse and recycling. If the growth of some MSs was lower than that of others, the value registered by the RV decreased. In absolute terms, the parameter increased, but the normalised values did not show the same effect. Table 1 proposes the WCI broken down into its three components inherently the five countries that always occupy the top five positions in the ranking (only Finland is sixth in 2014).

Following results are referred to these five countries. In all of these MSs, GDP PPS increased, resulting in 3148 billion PPS (+12%) in Germany, 376 billion PPS (+13%) in Sweden, 230 billion PPS (+16%) in Denmark, 190 billion PPS (+14%) in Finland and 111 billion PPS in Bulgaria (+19%) during 2014–2018 period. Population increased in Germany (+3%, 82,906 thousand inhabitants), Sweden (+5%, 10,175 thousand inhabitants), Denmark (+3%, 5794 thousand inhabitants),

Table 1
Top five countries during 2014–2018 period. Three components of WCI are proposed for each MS.

	2018	2017	2016	2015	2014
	Denmark				
WCI – WEEE	20.8	24.0	21.7	22.1	23.2
WCI – ELV	21.5	22.7	21.0	24.2	23.9
WCI - MSW	24.2	20.8	19.8	18.1	19.0
	Finland				
WCI – WEEE	29.7	28.4	22.0	26.2	27.6
WCI – ELV	19.6	21.2	23.1	22.0	21.7
WCI - MSW	16.5	14.2	15.2	14.0	8.5
	Bulgaria				
WCI – WEEE	20.5	23.6	21.6	25.5	21.5
WCI – ELV	24.5	26.0	25.7	26.3	25.9
WCI - MSW	19.7	18.4	14.3	11.8	15.2
	Germany				
WCI – WEEE	21.9	20.7	17.3	13.2	16.9
WCI – ELV	10.9	11.5	11.5	12.6	13.4
WCI - MSW	31.8	31.8	31.8	30.8	31.8
	Sweden				
WCI – WEEE	27.1	26.4	25.9	24.9	28.9
WCI – ELV	22.3	22.7	25.3	25.8	26.1
WCI - MSW	13.7	14.8	14.7	14.0	15.4

and Finland (+1%, 5516 thousand inhabitants). In contrast, a population reduction was verified in Bulgaria (−3%, 7025 thousand inhabitants).

Germany reached 24.7 million tonnes of recycled MSWs and its performance was so strong at the European level that it always reached a value above 30 in terms of WCI-MSW. It is precisely this strong performance that determines the low results of the other countries compared to Germany: ranging from 14 in Sweden to 24 in Denmark. However, Germany while maintaining a leading position presents a situation to be monitored: from 2014 to 2018 the generated MSW has increased from 519 to 606 kg per capita, while the recycled has remained about the same at 298 kg per capita. Regarding the other two waste types: +15.4% for ELV and + 19.9% for WEEE in terms of quantity reused/recycled. However, the specific data of the percentages show an opposite behavior: ELV_{per} (from 90% to 87%) and $WEEE_{per}$ (from 84% to 86%).

Sweden was a leader in the first 3 years of the period analyzed and was hyper performing in ELVs in 2018 recording 232 thousand tonnes of waste reused/recycled with +15.4%. This is also noted by ELV_{per} which increased from 84% to 86.8%. Opposite situation was noted for the other two waste categories: MSW_{per} from 33% to 30% and $WEEE_{per}$ from 84% to 83%. The negative data of MSW that determined the removal from the first three positions was due to the reduction of recycled waste (−6.9%). WEEE also showed a reduction, but a smaller one of 1.3% so that Sweden went from 12.6 to 11.8 kg per capita.

Finland was the only one of these five countries with a positive WCI Δ change. This was mainly due to two reasons: MSW_{cap} increased from 87 to 161 kg per capita reaching 886 thousand tonnes of MSW recycled (+86.9%) and $WEEE_{per}$ increased from 88% to 90% reaching 59.8 thousand tonnes of WEEE reused/recycled (+3.1%). The equivalent in terms of ELV was 107 thousand tonnes with an increase of 27%, but the WCI-ELV does not increase because the growth of the generated quantity was higher (ELV_{per} remains stable at 82.8%).

Bulgaria's performance results were primarily due to ELVs. The quantity reused/recycled reached 98 thousand tons (+25.5% with an increase of ELV_{per} from 94% to 95%). However, positive results were also registered for the other two types of waste. In fact, the MSW_{per} went from 21% to 30% for a share of recycled waste equal to 849 thousand tonnes (+25.4%). There is also a + 18.7% in terms of WEEE reused/recycled, but WCI-WEEE decreases due to a reduction in $WEEE_{per}$ from 85% to 81% that is not balanced by the increase in $WEEE_{cap}$ from 5 to 6.1 kg per capita (remember that for this country there was a reduction in population).

Denmark, as highlighted, occupies the first position of the ranking in 2018 and together with Bulgaria is the country that presented a balance between the three components. In particular, the best performing result was related to MSW with an increase of 27.3% of recycled waste to reach a value of 1525 thousand tons. The MSW_{cap} increased from 212 to 263 kg per capita and the MSW_{per} from 27% to 32%. The ELV component also increased: ELV_{per} increased from 86% to 90% reaching a recycled/reused quantity of 123 thousand tons (+20.5%). Finally, the situation is different for WEEE as the quantity reused/recycled was 58 thousand tons (−2.6%) and the $WEEE_{per}$ was reduced from 83% to 81%.

The new WCI proposed to quantify recycling and reuse activities in the waste sector can play a key role in the circular transition. In fact, multi-criteria analysis can consider multiple waste streams and dimensions. The immediately visible result of an index is to provide a ranking between different alternatives and to be able to compare their performance. However, such an analysis can be the input for more in-depth analyses in which the impact of other factors, such as technology and policy, can be assessed. In addition, this index can be split into its components in order to evaluate the individual impact on the result, and it is possible to propose a clustering of countries not only based on better or worse performance compared to the average value. This model also makes it possible to monitor changes in individual countries year by year and to assess the possible impact of specific policies. These issues will need to be explored in future analyses.

4.4. Clustering of European countries

The monitoring of trends is crucial, and progress against sustainable goals must be checked through deep and timely data collection over time. To this end, the definition of new indices, considering multiple aspects of performance, is critical for generating practical implications for decision-making.

Considering single waste streams, the present results point to some interesting conclusions. Both ELVs and WEEE showed high percentages of recycle and reuse – generally over 80% – which continuously grew (see Appendix for details), due to stringent indices defined by the related ELVs and WEEE directives. Likewise, the MSW index showed (on average) an increase during the 2014–2018 interval, with MSs that performed highest in MSW also performing better in overall waste management. However, these performances could be further improved by the adoption of innovative recycling technologies, especially considering the increasing sophistication of waste products. In this way, environmental and economic performances might achieve a more beneficial impact.

The present work clustered MSs through an analysis based on two perspectives (see Table 2). The first considered the EU 28 mean WCI as a reference level and divided MSs into two groups: i) MSs with a total WCI greater than the EU 28 mean (U) and ii) MSs with a total WCI lower than the EU 28 mean (D). The second perspective considered the total value related to each waste source. In analysing the data via these two perspectives, six groups were identified.

Group U (Up) included: a) MSs with a value greater than the EU 28 mean in all three waste sources (U3), b) MSs with only two out of three values greater than the EU 28 means (U2) and c) MSs with only one out of three values greater than the EU 28 means (U1).

Group D (Down) included: d) MSs with a value lower than the EU 28 mean in all three waste sources (D3), e) MSs with only two out of three values lower than the EU 28 means (D2) and f) MSs with only one out of three values lower than the EU 28 means (D1).

The WCI (WEEE), WCI (ELV) and WCI (MSW) values registered by each MS are reported in Tables B29–B33. Fig. 6 proposes the top five MSs, in terms of performance.

In 2018, the first group (U3) was represented by three MSs: Denmark, Bulgaria and Finland. Denmark was the only MS to maintain this placement over the entire 2014–2018 timeframe. In addition, the

Table 2
Clustering of European countries into six groups.

Year	2018				2017				2016				2015				2014			
MSs	Group	WEEE	ELV	MSW	Group	WEEE	ELV	MSW	Group	WEEE	ELV	MSW	Group	WEEE	ELV	MSW	Group	WEEE	ELV	MSW
SE	U2	■	■		U2	■	■		U2	■	■		U2	■	■		U3	■	■	■
DK	U3	■	■	■	U3	■	■	■	U3	■	■	■	U3	■	■	■	U3	■	■	■
BG	U3	■	■	■	U3	■	■	■	U2	■	■		U2	■	■		U3	■	■	■
DE	U2	■		■	U2	■		■	U2	■		■	U1			■	U2	■		■
FI	U3	■	■	■	U2	■	■		U3	■	■	■	U2	■	■		U2	■	■	
UK	U2	■	■		U2	■	■		U2	■	■		U2	■	■		U2	■	■	
IE	U2	■	■		U1		■		U3	■	■	■	U2	■		■	U3	■	■	■
HR	U2	■	■		U2	■	■		U1	■			D2	■			D2	■		
CZ	U2	■	■		U2	■	■		U2	■	■		D1	■	■		D2	■		
EE	U2	■	■		D2		■		U1	■			D2		■		D2		■	
FR	U1		■		U2	■	■		U2	■	■		U2	■	■		U2	■	■	
SI	U1			■	U1			■	U1			■	U1			■	D2			■
IT	D2		■		U1		■		D2		■		U1		■		D2		■	
PL	U2	■	■		D2		■		D2		■		D2		■		D2		■	
BE	D2		■		D2		■		D3				U2	■		■	U3	■	■	■
LT	D2		■		D2		■		D2		■		D2		■		U2	■	■	
LU	D1	■		■	D1	■		■	D3				D1	■		■	D1	■		■
NL	D3				D3				D3				D2	■			D2	■		
ES	D2		■		D2		■		D2		■		D2		■		D2		■	
AT	D2	■			D2	■			D3				D2	■			D2	■		
SK	D2	■			D3				D3				D3				D2	■		
HU	D3				D3				D3				D3				D2	■		
PT	D3				D3				D3				D3				D3			
EL	D3				D3				D3				D2	■			D3			
CY	D3				D3				D3				D3				D2		■	
LV	D3				D3				D3				D3				D3			
MT	D3				D3				D2	■			D2	■			D2	■		
RO	D3				D3				D3				D3				D3			

U1, U2, and U3 are above the European average, while D1, D2, and D3 are below the European average. In addition, the symbol "■" indicates that the specific value is higher than the European average. The analysis is proposed for three years.

Fig. 6. Top five performing MSs in 2018 as a function of the three dimensions. Croatia is first in WEEE (first in $WEEE_{gdp}$ and $WEEE_{per}$), Bulgaria in ELV (first in ELV_{gdp} and has a high value in ELV_{per}) and Germany in MSW (first in all three dimensions).

weight composition of their WCI was peculiar. Denmark was one of the top five MSs in terms of MSW management (occupying the third position with 24.2) and ELV management (occupying the fifth position with 21.5), while its score was slightly lower in WEEE (occupying the eighth position with 20.8). Bulgaria occupied the first position in terms of ELV with 24.5. However, the value obtained does not always correspond to a better ranking position. The value of MSW management (19.7) was lower than that of WEEE (20.5) and the respective ranking positions were fourth and eleventh, respectively. The reason for this should be not associated to the best performer, but to the distribution of several values. In fact, the highest ELV management value of 24.5 is remarkably smaller than the other waste streams. Germany's performance in MSW management reached 31.8 and Croatia's performance in WEEE management showed 33.7. Bulgaria presented 20.5 in WEEE management (thus close to Denmark's value) but a ranking that placed it eleventh. Finally, with 19.7, it ranked fourth in MSW management. This country in 2015–2016 had a lower performance than the European average in terms of MSW management but in recent years has improved its recycling rate (from 19% to 30%). Finland was within the top five countries only in WEEE management with 29.7 (occupying the second position) and showed a situation similar to the one seen before: 16.5 in MSW management (occupying the sixth position) and 19.6 in ELV management (occupying the ninth position). Also, this country had a lower performance than the European mean in terms of MSW management during the years 2014, 2015 and 2017. It was not characterized by an increase of recycling rate (stable around 29%), but recycled waste shifted from 147 a 161 kg per capita in 2018 than 2017.

In 2018, the second group (U2) was constituted by eight MSs: Sweden, Germany, the United Kingdom, Ireland, Croatia, Czechia Estonia and Poland. Of this group, only Germany had a value below the European average for ELV, while all others for MSW management. The reason is that while for WEEE and ELV there are fourteen and fifteen countries above the European average, for MSW there are only six. In addition, Sweden occupied the fourth position in both WCI-WEEE and WCI-ELV (27.1 and 22.3, respectively); the United Kingdom followed Croatia in WEEE management with 27.5; Ireland was second in ELV management with 23.8 and Germany, as above-cited, was leader in MSW management. In addition, it is necessary to highlight the performance of Poland, which unlike the other MSs, is new to this group as the good performance of ELVs had been matched by that of MSWs with a recycling rate increasing from 82.7% to 87.6% in 2017–2018.

The third group (U1) included France and Slovenia, thus completing the list of MSs with a general WCI value greater than the EU 28 mean in 2018. Slovenia throughout the period considered presented an excellent performance in terms of MSW management occupying the second position with 26.4 in 2018. France on the other hand was still in the U2 group with a third place in the ELV ranking with 23.2. The deterioration was recorded in the WEEE management where the percentage of recycled waste moved from 81.9% to 74.2% in the period 2017–2018. Only Luxembourg was placed in the fourth group (D3). Rather, six and eight MSs were present in the fifth (D2) and sixth (D1) groups, respectively. Among them, only Portugal, Latvia and Romania always registered lower values than the EU 28 mean and it was registered also in all three components.

Some authors showed a correlation between GDP and the amount of MSW generated in Italy and the UK, while it was not verified in Greece (Malinauskaite et al., 2017). However, some countries (i.e. Poland) had a low amount of waste generated. One possible reason was associated with the potential role of illegal dumping (Malinauskaite et al., 2017). The same study highlighted as the definition of MSW is not uniform in all the European countries (i.e. Estonia and Latvia). This highlights a critical element, as the uncertainty of statistical data. High landfill use penalised the environmental performance of countries (such as Greece and Poland), while France had a high level of recycling and low environmental impact from an energy point of view considering its energy mix dominated by nuclear power (Andreasi Bassi et al., 2017). The growing waste generation affected several European countries, but the most significant reduction in the last 10 years was evident in Romania, Bulgaria and Spain. Results show as these countries are present in different clusters (Minelgaitė and Liobikienė, 2019). A comparison of European countries is much smaller in literature when considering the other two waste categories. About ELVs, Bulgaria, Ireland and United Kingdom had very significant performances. However, a study highlighted as Western European countries export significant amounts of waste towards Eastern European countries (or outside Europe) (D'Adamo et al., 2020b). The next step towards data processing should be the quantification of these waste flows at least among European countries, in order to reduce uncertainty. There is a dependency between WEEE generation and GDP PPS and the analysis shows higher values in Western European countries for both variables than in Eastern European countries (Boubellouta and Kusch-Brandt, 2021; Kusch and Hills, 2017). Some previous analyses highlighted the positive performance of some countries (such as Sweden, Denmark and Finland), but this study provides additional results (Awasthi et al., 2018a).

In conclusion, it is possible to confirm that the posed research question has been evaluated from multiple perspectives. Starting from a significant number of input data (and through the proposed approach) it was possible to simplify the picture and provide trends on how waste management evolved in Europe. The research can be improved by incorporating a larger number of years (e.g. available from 2017 onwards) and other waste streams (e.g., construction demolition waste). However, the WCI is the basis from which to start. Even if there are some limitations, this work tried to fill in a literature gap. By proposing an index able to aggregate different waste categories, it is possible to compare different timeframes and identify specific clusters. However, further analysis is required, especially from the point of view of which policies can be implemented in order to foster circular economy models. The circular economy is an epochal change, and it will not only be necessary to recycle and reuse, but to do it well. In this context, the identification of indexes will play a key role in making sustainable both supply and demand side.

5. Conclusions

The research question of this work was answered through the proposition of a new index, Waste Circularity Index (WCI), which was generated by a weighted average of three sub-indices, each dedicated to a different waste stream. The AHP methodology, involving experts, provided weights for WEEE, ELVs and MSW. This method was selected due to the complexity involved in defining an index for the reuse and recycling of waste, wherein the assessment of waste prevention (e.g. the definition of the level of protection for humans and the environment, as well as the level of resource conservation) was not always quantifiable. In the research, illegal flows of waste streams represented a black box, producing significant deviations in the results. However, the adoption of EoL strategies (and the assessment of the economic and environmental impacts of different waste streams) was identified as a crucial step towards the development of CE models.

To simplify the comparison, an average value of the 28 MSs was used as a reference, aimed at separating the MSs into two groups. The results demonstrated that EU waste management directives have played a key role in supporting the development of new waste management actions around Europe. However, for more ambitious goals to be achieved, the EU may need to increase sensitivity to these themes among citizens and governments, for example by linking waste management performance to a set of penalties to be paid by non-compliant MSs (e.g. when none of the three sub-indices is satisfied). Another suggestion would be to award prizes to virtuous countries.

The results showed that several MSs had adopted positive EoL practices with respect to some waste streams, while others presented the opposite situation. This could represent a limitation for the present research, providing a false signal. For example, western MSs tended to export their ELVs to eastern MSs (and extra-EU countries), where they were eventually recycled. This droves up collection and recycling rates per capita (and per unit of GDP) in the importing states, whereas it tended to lower these rates in the exporting states. This explains why countries such as Bulgaria, Czechia, Poland and others scored above the EU 28 mean in terms of ELVs, while countries such as Belgium and Germany scored below. A similar observation might hold true for WEEE, as was already assessed in other works (Boubellouta and Kusch-Brandt, 2021). This way, the position of a certain country in a certain cluster cannot always be directly linked with the effectiveness of the adopted environmental policies. Various MSs tended to export e-wastes to developing and underdeveloped countries outside the EU (e.g. China and Ghana), with unclear waste management practices. As there are no tools available to estimate these flows, this aspect must be integrated within new EU directives in order to identify effective solutions (Pacini et al., 2021). Furthermore, the WCI did not measure waste prevention, but it provided some insights into reuse and recycling. This work is based on real data, so if a country has a high level of recycled waste, it is a good sign. However, if the waste it handles is not produced in its own country but comes from other countries, whose responsibility is it? A country that recycles significantly, but without a proper supply chain model, without state-of-the-art technology is not able to generate economic growth. However, this can also be associated with the quality of the waste that is received, with its added value. Furthermore, what can be said about those countries that export their waste? This work has shown that there is an urgent need to control the borders between countries, but also the journeys to poorer countries. Sustainability inevitably comes down to the direction in which each country must take responsibility for the waste it produces.

Some of the results of this study could make some countries very recycling conscious. However, this study wants to highlight how this can be achieved if no attention is paid to the flow of waste between countries. This practice undermines the circularity of resources, it is necessary to put a brake on this aspect because each territory must be equipped with advanced technologies to dispose of waste in a sustainable manner and all stakeholders are called both in production and consumption phase to virtuous behavior. If we add to this aspect the illegal traffic we understand why the dark business is increasingly interested in waste. The development of indicators has the merit of photographing a situation and highlighting the real values that characterize individual countries. So this study wants to give credit to those countries that achieve high performance because they dispose of waste internally. On the other hand, it refers to future considerations both for those countries that have high recycling rates but dispose of waste from other countries and for those countries that tend to send the waste they produce beyond their national borders. Resource circularity requires careful monitoring of data and penalties for those who transgress the patterns of non-self-recovery and reuse of waste.

The present work suffered from some limitations that might be resolved in future research: i) not all categories of waste were included in the new index (e.g. construction and demolition waste), ii) the research did not include economic, environmental and social analyses (e.g. in terms of profits, reductions in emissions and job opportunities respectively), iii) the impact of innovation (e.g. the technological improvement of recycling processes) was not considered and iv) the impact of uncertainty by conducting statistical analyses of how different variables are related to each other and whether these relationships are verified across countries. Furthermore, new studies are necessary to measure the impact on citizens and firms related to a proper waste management.

This paper has presented a new WCI based on AHP methodology and applied it to a case study of the EU. The same method could – and should – be replicated in other territories, to facilitate international comparisons at all levels. For this purpose, input data for all components of the index will be needed.

Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2021.106730.

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