Waste Management 128 (2021) 154–166

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

An integrated approach of PCA and PROMETHEE in spatial assessment of circular economy indicators

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ARTICLE INFO

Article history:
Received 23 February 2021
Revised 15 April 2021
Accepted 27 April 2021

Keywords:
Circular economy
Sustainable development
Environmental sustainability
Principal component analysis
PROMETHEE method

ABSTRACT

In order to ensure environmental sustainability, reducing the consumption of renewable resources, finding adequate substitutes for non-renewable resources, and reducing the generation of waste and pollution are necessities. The concept of circular economy one of the possible and good responses to improve the sustainability of the system, as it places particular emphasis on the reduction, reutilization and recycling of its elements. The paper presents a comparative analysis of the circular economy development in European Union countries based on the dataset encompasses 11 indicators, covering the seven-year period with biennial data. The analysis was performed using the integrated approach of the Principal Component Analysis and PROMETHEE with the aim of creating a composite index as a measure of the development of the circular economy at the national level. The ranking outcomes indicate that during the observed period Germany has the most developed circular economy, followed by the Netherlands, France and Austria. Additionally, the results of the research clearly indicate the positive correlation between the development of circular economies at the national level and the socio-economic development of the country, while progress in the circular economy has no immediate impact on environmental sustainability, but the effects are realized subsequently, with the intensity of the relationship increasing in two-year lag periods.

1. Introduction

There are different views concerning the beginnings of the circular economy concept. Most of the scholars agree that the circular economy term was introduced by environmental economists Pearce and Turner (Pearce, 1990) to deal with the interconnections of the main economic functions of the environment (Andersen, 2007): (i) a life-support system; (ii) a sink for residual flows; (iii) a resource base for the economy; (iv) amenity values.

World Economic Forum (MacArthur and Company, 2014) defines circular economy as a system that is regenerative or restorative by purpose and design, and that replaces the concept of end-of-life with restoration, eradicates usage of toxic chemicals that hinder the reuse and return to the biosphere, redirects to the usage of renewable energy, and aspires to eliminate waste through superior design of systems, products, materials and business models. Unlike the present linear economy, the circular economy is considered to be a viable economic system in which growth of the economy is dissociated from the use of resources, via the recirculation and reduction of natural resources (Corona et al., 2019). Preservation of natural capital is one of the main focuses of the circular economy (Kurita and Managi, 2021). Additionally, the fact that the successful implementation of the circular economy contributes to all three dimensions of sustainable development should not be overlooked (Korhonen et al., 2018).

The strategic orientation of the European Union (EU) towards the circular economy was confirmed by the adoption of the European Union's Circular Economy Action Plan in 2015 (European Commission, 2020a). As a result of the actions aimed at creating circularity, the EU expects the improvement of competitiveness and economic growth, as well as creation of jobs, while decreasing the environmental impact and dependence on resources (Calisto Friant et al., 2021).

With an intention to create a transition from linear economy to circular economy, numerous approaches have been proposed. To evaluate the usefulness of these approaches it is important to

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https://doi.org/10.1016/j.wasman.2021.04.057
0956-053X/

assess the level of circular economy development using an appropriate circularity metrics. Corona et al. (Corona et al., 2019) categorized existing circularity metrics into two sets: (i) circularity indices designed to evaluate the circularity level of the system; (ii) circularity assessment tools focus on the analysis of the influence of circular policies to the circular economy principles. The second group has two sub-groups: (a) circular economy assessment indicators and (b) circular economy assessment frameworks. Differences among circularity metrics also emerge from the level of the analysis. Various circular economy metrics are developed and commonly grouped into three categories (Pauliuk, 2018): macro-level (municipal, province, district, or country), meso-level (industry), and micro-level (enterprises, clients, products). Reviews of different indicators applied for circular economy assessment on different levels are presented in several papers (Banaitė, 2016; De Pascale et al., 2020; Geng et al., 2012; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2017; Sassanelli et al., 2019; Su et al., 2013). The largest part of research studies was addressed towards the proposition of an appropriate circularity metrics for the micro and meso-level (Franklin-Johnson et al., 2016; Huysman et al., 2017; Janik and Ryszko, 2019; Kristensen and Mosgaard, 2020; Li and Su, 2012; Yang et al., 2011). Regarding macro-level, there are several proposed indicators for the circularity measurement (EASAC, 2016; EEA, 2016; Geng et al., 2013; 2012; Giannakitsidou et al., 2020; Jia and Zhang, 2011; Mayer et al., 2019; Su et al., 2013; Wang et al., 2020). Nonetheless, the existing circularity metrics face criticism because they do not embody the multidisciplinary and systemic character of the circular economy (Saidani et al., 2017).

Although recognizing variety of already developed metrics that may be applied in the assessment of circularity, this paper concentrates on the development of a novel approach, based on the statistic and multi-criteria decision-making (MCDM) methods for the assessment of circular economy development on a country level. Multidimensionality of a specific phenomenon introduces the necessity to create composite indicators as a measurement approach (Bogdanov et al., 2019) and the paper is aimed to offer methodological framework for creating circular economy development index.

The paper aims to provide spatial assessment of circular economy indicators in EU countries in order to determine countries with the most developed circular economy systems, as well as the countries with the fastest growing circular economy in the last decade. To achieve the stated aim, dataset consisting of 11 indicators will be analysed using the Principal Component Analysis (PCA) and PROMETHEE method. The data coverage period is six years, with three annual measurements every other year.

The remainder of the paper is organized as follows: after introductory remarks, a literature review on the application of the MCDM methods for environmental sustainability, along with the PCA and the PROMETHEE method will be presented. In the next section, model development will be explained, followed by the presentation and discussion of the results obtained by the multi-criteria analysis. Lastly, concluding remarks will be offered.

2. Literature review

The use of multi-criteria analysis methods in the field of sustainability has an upward trend in the recent decades, primarily because during the assessment of sustainability a large number of diverse criteria needs to be considered. Therefore, this section reviews the usage of multi-criteria analysis methods in the field of environmental sustainability, and additionally offers the methodological basis of Principal Component Analysis and PROMETHEE method.

2.1. Application of MCDM methods in the environmental sustainability assessment

Adequate definition of environmental sustainability requires review of the sustainable development concept and the definition of sustainability itself. Sustainability represents the capability to continue particular behaviour indeterminately (Health Organization Regional Office for Europe, 2015). Likewise, a development that meets the needs of the present without compromising the ability of future generations to meet their own needs is a sustainable development (World Commission on Environment and Development, 2017). Decision-making in sustainable development frameworks presents a demanding task that should assurance a long-standing equilibrium among environmental preservation, economic efficiency and social equality (Frini and Benamor, 2018).

To achieve sustainability, sustainable development main pillars must be taken into account concurrently during the process of decision-making, leading to the decisions to be environmentally acceptable, socially equal and economically efficient (Frini and Ben Amor, 2019). Nevertheless, the most important of these pillars is the one related to environmental sustainability, since the other two pillars depend on the environment in which they are located. Environmental sustainability can be defined as an assembly of restraints on the main activities of human economic subsystem: usage of non-renewable and renewable resources on the source side, and assimilation of waste and pollution on the output side (Goodland, 1995). In other words, environmental sustainability is the capability to preserve harvest rates of renewable resources within regenerative capacities, rates of depletion of non-renewable resources ought to be established under the rate at which renewable alternatives are created, and pollution creation and emissions of waste should not surpass the assimilative capacity of the local environment (Rogers and Daly, 1996). Creating an adequate response to different environmental issues is a task that is, by nature, multi-criteria processes that require the mutual consideration of different social, economic and environmental criteria during the decision-making process (Khalili and Duecker, 2013). Given the multi-criteria nature of the problem, it is not surprising that there is a growing body of research focusing on the application of multi-criteria analysis methods in the assessment of environmental sustainability. MCDM techniques are becoming increasingly popular when it comes to ranking and ordering of alternatives under sustainability conditions primarily because they take into account the conflicting criteria expressed by different units of measure, which is a characteristic of a real-world problems (Li, 2012). There is a number of MCDM techniques, most of which can be and have been applied for the assessment of environmental sustainability. These techniques can broadly be categorized into several groups (Hajkowicz and Collins, 2007):

1) Multi-attribute utility and value functions. This group encompasses methods that seek to express decision makers' preferences by using utility/value functions (de Brito and Evers, 2015). Common techniques include: Simple multi-attribute rating technique (SMART), Multi-attribute value theory (MAVT) and Multi-attribute utility theory (MAUT). The key advantage of utility approach is that it takes uncertainty into account (Velasquez and Hester, 2013). These methods have compensatory nature and are widely accepted in the sustainability assessments. A comprehensive overview of the application of utility methods in forest management and planning is presented in Ananda and Herath (2009). Simsek et al. (2018) presented an analysis of multi criteria decision methods and indicators of sustainability under several pillars: environmental, social economic, technical and risk. In addition, sustainability assessment of

international clean development mechanism concentrated solar power projects was implemented via MAUT method. Dantsis et al. (2010) employed the MAVT to evaluate and make comparison among the achieved sustainability of production systems of agricultural plant in two geographical regions in Greece.

2) Pairwise comparisons. The essence of the approaches in this group is to conduct pairwise comparison of the criteria and alternatives by expressing preferences against a predefined scale. Among the popular methods are: Analytical Hierarchy Process (AHP), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), and Analytical Network Process (ANP). Overview of application of AHP in strategic forest planning is presented in Ananda and Herath (2009). Giamalaki and Tsoutsos (2019) presented and tested a methodology for assessment of the most appropriate locations for placement of solar power systems by engaging Geographical Information Systems and the AHP. Lavoie et al. (2016) presented a method for systematically evaluation of the ecological value of all 1347 wetland complexes in Quebec City and created an index via the MACBETH approach. Xu et al. (2015) examined the interlinkage of sustainable building energy efficiency retrofit by focusing on an existing hotel building by applying energy performance contracting mechanism and an effective ANP approach. Lam and Lai (2015) developed a model for the assessment of environmental sustainability of shipping companies operations by using an integrated ANP and Quality Function Deployment approach. Atmaca and Basar (2012) evaluated the suitability of present and planned power plants in Turkey by applying ANP on a sample of six different energy plants considering criteria such as life quality, economical suitability, technology and sustainability, and socio-economic effects. Mahdiyar et al. (2019) created a decision support system for choosing the optimal green roof type for residential buildings in Kuala Lumpur by employing fuzzy Delphi method and cybernetic fuzzy ANP.
3) Outranking methods. Outranking approaches involve determination of the degree of dominance among alternatives based on the relationship of preferences whereby as a result a partial preference ranking of the alternatives is established rather than a cardinal measure of their preference relationship (Penadés-Plà et al., 2016). These methods include: ELECTRE and PROMETHEE. A comprehensive overview of the PROMETHEE method applications in the field of environmental management is given in Behzadian et al. (2010). Regarding circular economy, the number of researches that employ PROMETHEE methodology is limited. Lolli et al. (2016) have presented a novel group fuzzy PROMETHEE method in order to combine economic and social criteria with the usual environmental criteria of life cycle evaluations. The proposed approach was employed to the selection of the finest solution for waste treatment in the nature park. Betrie et al. (2013) have applied PROMETHEE based model to evaluate and select remedial alternatives for mine sites. Oberschmidt et al. (2010) have applied PROMETHEE approach together with the life cycle concept to estimate the influence of energy supply technologies. An overview of ELECTRE method applications in the area of environmental management and natural resources is presented in Govindan and Jepsen (2016).
4) Distance to ideal-point approaches. The essence of ideal-point methods is the determination of the feasible solution which minimizes the distance to certain ideal point previously specified in the value space (Carrizosa et al., 1997). An optimal solution corresponds to the alternative that has the smallest distance from the ideal point. Common methods include: TOPSIS and VIKOR method. An overview of TOPSIS method applications in the field of environment management is given in Behzadian et al. (2012).Wide-ranging overview of VIKOR method applications in the environmental management area is presented in Gul et al. (2016).
5) Other methods. These methods include customized methods that generally extend or adjust an original method to a specific application, along with hybrid and fuzzy approaches (de Brito and Evers, 2015).

One of the frequent applications of the MCDM method in the analysis of environmental problems is in the creation of composite indices, as a modern approach to assessing the sustainability of a system. According to Freudenberg (2003) construction of composite indices is a very complex iterative process, which includes a number of demanding steps among which are: (1) systematization of the theoretical framework for identification of relevant dimensions of analysis, i.e. identification of relevant indicators to be included in composite index; (2) values of individual indicators, with the aim of transforming them into pure data, undetermined by units of measurement, as well as to integrate indicators of opposite polarity, i.e. indicators whose higher value is contrary to the value of higher values of composite index to allow comparisons, (3) insertion of missing data, through an appropriate mathematical-statistical procedure, (4) weighting of individual indicators and as a final step (5) sensitivity analysis to robust aggregation.

The critical step of the entire process of creating a composite index is to determine the relative importance or weights of individual indicators in order to merge them into a single measure, such as the composite index. The context of such problem imposes two main issues to consider: the first, methodology to determine the weighting coefficients, or whether in this process to use subjective or objective approach, and second, whether the created composite index is characterized by a compensatory effect between individual indicators, that is, whether the composite index is created in such a way that it is possible to compensate the lack of one individual indicator, with a sufficiently large advantage of another (Fusco, 2015). This paper uses an objective approach in determining the weights of individual indicators, in order to determine the significance of each of the indicators of the circular economy. Subjective approach in determining the weight coefficients are largely relies on pairwise comparisons methods and it is suitable to be applied in situations where the subjective perception of decision-makers is relevant to a given problem (Ranđelović et al., 2018). As all indicators that describe the development of the circular economy are perceived as one group of factors, PCA is used for the purpose of analysing their mutual relationship and determining the significance (Ranđelović et al., 2013). Also, one of the aggregation goals is to mitigate the compensatory effects in created composite measure and therefore the method of choice is PROMETHEE.

An additional reason for the application of the PROMETHEE method in this paper is that for its application, in addition to certain weighting coefficients, each indicator must be accompanied by appropriate parameters (thresholds, or pseudo-criteria). This method does not require normalization before aggregation of variables, because they use source data for comparison, and source data on various indicators of the circular economy can be included.

2.2. Cluster analysis

Cluster analysis can be applied to detect the relationship that exists between heterogeneous units and group them into relatively homogeneous sets. Conducting cluster analysis first involves selecting the appropriate cluster procedure, whereby agglomerative hierarchical cluster analysis will be applied in this paper. The essence of this approach is in the application of a bottom-up strategy, where each object initially represents a separate cluster, and then iteratively the objects join the previously formed groups of objects or form a new group with another object (Jafarzadegan et al., 2019). The agglomerative hierarchical clustering algorithm is one of the basic clustering algorithms due to its good computational stability, and is implemented through several steps (Govender and Sivakumar, 2020): (i) defining each object as a separate cluster; (ii) determining the distance between clusters; (iii) combining two clusters with a minimum distance and recalculating new distances between clusters; (iv) repeating steps (ii) and (iii) until there is only one cluster containing all the objects.

The square Euclidean distance will be used to determine the distance between objects, while the grouping of objects will be performed using Ward's procedure. The Ward's linkage shows certain advantages over other linkage methods, which are reflected in increasing homogeneity within the cluster, reducing heterogeneity between clusters and increasing the robustness of the results (Ünal and Shao, 2018). In addition, there is evidence that the application of the Ward method in combination with the squared Euclidean distance creates clusters with the lowest sum of squares error (Punj and Stewart, 1983).

2.3. Principal component analysis (PCA)

The PCA has been widely employed in the composite indicators construction, created based on the correlation among the sub-indicators (Saisana and Tarantola, 2002). PCA and more precisely factor analysis (FA) can congregate collinear indicators to create a composite indicator that should contain as much common information about these indicators as possible (Competence Centre on Composite Indicators and Scoreboards, 2020). This analysis, together with FA, correlation analysis, regression analysis, or data envelopment analysis, belongs to so-called 'data-driven techniques' (Greco et al., 2019). The objective of using those methods is to combine sub-indicators into composite indicators while at the same time the maximum share of the overall variation in the sample is explained. The PCA aims to extract the greatest variance with each element from a data set. The first element is created on the basis of a linear combination of variables under observation that maximally splits the subjects through maximizing the variance of the results of their elements. Based on the residual correlations, a second element is formed, while the following elements, likewise, extract the maximum variability from the residual correlations. (Tabachnick and Fidell, 2012). Such, PCA helps in overcoming the overfitting issue by reducing the number of variables, which is one of the advantages of its application. Another advantage is reflected in the fact that, after implementing PCA, all principal components are independent of one another.

In some situations, explanation of a considerable portion of the indicators' variance cannot be adequately performed on the basis of the first component alone. In that case additional components are required. Nicoletti et al. (2005) developed product market regulation indicators and chose PCA as the extraction method. As a result, several principal components were isolated. The authors applied varimax technique to rotate the components to reduce the quantity of indicators with great loadings on every single component.

El Emam et al. (1998) created Success of Software Process Improvement Index with the aim to identify the settings responsible for the failures or successes of software process enhancement endeavours. They used a set of 14 variables that have a significant impact on improving the software process. The authors believe that some of the variables can be combined into the same dimension since they measure the same setting. According to them, PCA represents a technique that can implement such reductions, considering the interactions between various explanatory variables. Finally, the composite indicator was obtained as the sum of the five main principal components that make up 67% of the total variance (Saisana and Tarantola, 2002).

The objective of PCA is to consider p standardized variables $X_1, X_2, \ldots, X_p$ and set up a linear combination to create uncorrelated principal components $Z_1, Z_2, \ldots, Z_p$, following

$$Z_j = \sum_{i=1}^{p} a_{ij} X_i, \mathrm{j} = 1, 2 \cdots \mathrm{p} \tag{1}$$

where a_{ij} are the weights which are chosen in the way that principal components Z_j meet several requirements: (i) principal components are uncorrelated; (ii) the greatest possible share of the variance of the set of p variables X_p is accounted by the first principal component, the maximum of the remaining variance is accounted by the second principal component and so on to the last principal component; and (iii) the sum of squared weights equals 1, i.e. $a_{1j}^2 + a_{2j}^2 + \cdots + a_{pj}^2 = 1, \mathrm{j} = 1, 2 \cdots \mathrm{p}$.

It is necessary to emphasize that finding the optimal main components requires prior standardization of the original variables. Otherwise, principal components will be biased towards features with high variance, leading to false results, which could be considered as a disadvantage of PCA (Kumar, 2019).

In the context of applying the Principal components method, the essence is in obtaining the corresponding eigenvalues (λ_p) of the sample covariance matrix **C** for which the following equality is satisfied:

$$\left|\mathbf{C} - \lambda_f \mathbf{I}\right| = \left| \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1p} \\ c_{21} & c_{22} & \cdots & c_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ c_{p1} & c_{p2} & \cdots & c_{pp} \end{bmatrix} - \lambda_p \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \right|$$
$$= \left| \begin{bmatrix} c_{11} - \lambda_1 & c_{12} & \cdots & c_{1p} \\ c_{21} & c_{22} - \lambda_2 & \cdots & c_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ c_{p1} & c_{p2} & \cdots & c_{pp} - \lambda_p \end{bmatrix} \right| \tag{2}$$

The eigenvalues of the matrix C represent the principal components' variances. Loadings are represented by the correlation coefficients of the variables X_p with the principal components Z_j (Tabachnick and Fidell, 2012). Using the matrix of factor loadings, it is possible to construct the weights bearing in mind that the square of factor loadings denotes the share of the overall attribute variance rationalized by the component (factor).

2.4. PROMETHEE method

PROMETHEE method belongs to the group of outranking approaches, whose main advantage is that they do not require normalization of criteria and are not compensatory (Ishizaka and Nemery, 2013).

PROMETHEE method was originally proposed by Brans (1982) and additionally developed by Brans and Vincke (1985). There are varieties of PROMETHEE method developed over the years (Brans and Mareschal, 2005): PROMETHEE I-VI and PROMETHEE GAIA.

In this paper the PROMETHEE II approach was selected due to its stability, clarity and simplicity (Athawale and Chakraborty, 2010). The essence of the PROMETHEE II approach is a pair-wise comparison of the alternatives according to different criteria (Behzadian et al., 2010).

To formulate the decision-making problem a set of alternatives A = {$a_1 \ldots a_m$} and a set of criteria G = {$g_1 \ldots g_n$} is considered. The outranking relations on each criterion among pairs of alternatives represent functions of the differences that the alternatives display on criterion j (Lolli et al., 2019).

In the first step the preference of an alternative a_i over an alternative a_j for each criterion g_k is determined:

$$d_k(a_i, a_j) = g_k(a_i) - g_k(a_j) \tag{3}$$

The results of this pairwise comparison are in the next step transformed to a preference degree based on the preference function P_k (Sarrazin et al., 2018). There is a possibility for decision maker to express the preference threshold p_k and the indifference threshold q_k for each criterion, which depends on the shape of the selected preference function (there are six main preference types (Brans et al., 1986): linear, level, V-shape, U-shape, usual, and the Gaussian).

$$P_k(a_i, a_j) = P_k[d_k(a_i, a_j)] \tag{4}$$

$$0 \leq P_k(a_i, a_j) \leq 1 \tag{5}$$

The global preference of a_i over a_j, $\pi(a_i, a_j)$ is obtained in the next step and represents a weighted sum of all preferences$P_k(a_i, a_j)$, wherein w_k is the relative importance of the j^{th} criterion.

$$\pi(a_i, a_j) = \sum_{k=1}^{j} P_k[d_k(a_i, a_j)] \cdot w_k \tag{6}$$

$$w_k \geq 0, \sum_{k=1}^{j} w_k = 1 \tag{7}$$

In the next step the calculation of the outranking flows of each alternative is calculated, where φ^+ and φ^- represent the positive flow score and the negative flow score, respectively.

$$\varphi^+(a_i) = \frac{1}{n-1} \sum_{x \epsilon A} \pi(a_i, x) \tag{8}$$

$$\varphi^-(a_i) = \frac{1}{n-1} \sum_{x \epsilon A} \pi(x, a_i) \tag{9}$$

Based on the above relations, the decision maker can simultaneously measure the preference of action a_i on average over the all remaining actions x of set A, and the preference of actions x , on average, over a_i (Sarrazin et al., 2018).

In the final step the net outranking flows are determined and represent the balance among the negative and the positive outranking flows ((Kabir and Sumi, 2014):

$$\varphi(a_i) = \varphi^+(a_i) - \varphi^+(a_i) \tag{10}$$

3. Data and model development

The research in the paper is based on empirical data on different aspects of circular economy framework, which are a part of official Eurostat databases (Eurostat, 2020a). The sources of the inputs for the stated framework are various: Eurostat, Joint Research Centre (JRC), the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), and European Patent Office.

Table 1
Structure of the sample.

Area	Countries included
Western Europe	Austria (AT), Belgium (BE), Germany (DE), France (FR), Ireland (IE), Netherlands (NL) Luxembourg (LU), United Kingdom (UK)
Central and Eastern Europe	Bulgaria (BG), Croatia (HR), Czech Republic (CZ), Estonia (EE), Hungary (HU), Latvia (LV), Lithuania (LT), Poland (PL), Romania (RO), Slovenia (SI), Slovakia (SK)
Northern Europe	Denmark (DK), Sweden (SE), Finland (FI)
Southern Europe	Spain (ES), Portugal (PT), Malta (MT), Greece (EL), Italy (IT), Cyprus (CY)
Total	28 countries in the sample

Source: Authors‘ preview.

It can be observed that, due to multidimensional nature of circular economy, there is no single measurement of the circular economy development. Nevertheless, there are several indicators established in order to capture the performance in various areas that contribute to the circular economy development. These indicators are designed to analyse the progress of EU member states in the process of transition from linear to the circular economy through reduced resource requirements, leading to increased resource security and reduced environmental pressure. The sample consists of 28 EU countries, divided into four areas (Table 1).

The assessment of circular economy development is conducted based on 11 indicators, grouped into following areas: (1) production and consumption, (2) waste management, (3) secondary raw materials, (4) competitiveness and innovation. The data coverage period is six years, with three annual measurements every other year: 2010, 2012, 2014 and 2016 (2018 was not included due to data unavailability for several indicators).

Production and consumption area (C1) encompass one indicator related to the generation of municipal waste per capita (C11). Municipal waste represent waste piled up and treated by or for municipalities (OECD, 2020). Municipal waste contains mainly waste produced by households, but may as well contain alike wastes produced by public institutions and small businesses and gathered by the municipality. According to the Eurostat (Eurostat, 2020b) in the total waste generated, municipal waste accounts for about 10%. For 2018, there is a large fluctuation in the municipal waste generation, ranging from 814 kg per capita in Denmark down to 272 kg per capita in Romania, mainly due to the dissimilarities in economic wealth and consumption patterns.

Waste management area (C2) includes several indicators: recycling rate of all waste excluding major mineral waste (C21), recycling rate of municipal waste (C22), recycling rate of packaging waste by type of packaging (C23), recycling of bio-waste (C24), recovery rate of construction and demolition waste (C25) and recycling rate of e-waste (C26).

Recycling rate of all waste excluding major mineral waste (C21) represents a percentage of waste recycled in entire waste treated, excluding major mineral wastes. Waste excluding major mineral wastes refers to waste that stem from all households and economic sectors, consequently containing waste generated from both production and consumption (European Environment Agency, 2020). Major mineral waste is not included in order to obtain better observation of trends in the ordinary waste generation, allowing for more meaningful comparison across countries (Eurostat, 2020c).

Recycling rate of municipal waste (C22) is determined as the ratio of the tonnage recycled from municipal waste and the entire quantity of municipal waste.

Recycling rate of packaging waste by type of packaging (C23) is computed as share of entire volume of recycled packaging waste, in the entire volume of created packaging waste. Considering the type of packing waste, greatest portion of the packing waste came from paper and cardboard (41%), followed by plastic and glass (19% each).

Recycling of bio-waste (C24) is computed as the proportion of composted/methanised municipal waste over the overall population and is expressed in kg per capita.

Recovery rate of construction and demolition waste (C25) represents the share of demolition and construction waste set for re-use, recycled or designated to material recovery in the entire demolition and construction waste.

Recycling rate of e-waste (C26) represents the percentage of e-waste, such as fridges, televisions, computers, and mobile phones that is recycled.

Secondary raw materials area (C3) includes indicators such as: trade in recyclable raw materials (C31) and circular material use rate (C32).

There is a possibility for re-introduction of recycled materials into the economy as new materials or goods. Yet, not all countries have the ability to cope with this type of waste and therefore, they export large portion of their recyclable waste to other countries. On the other hand, some countries have high capacity for dealing with this type of waste and are willing to import recyclable waste. As a proxy for trade in the recyclable materials a volume of imports from non-EU countries is used. Nevertheless, when it comes to waste trade, two sides must be taken into account: on the one side, directing waste to countries capable of safe waste treatment and management can improve the overall quality of the environment, while on the other side, directing waste to countries with poor environmental legislation may cause serious environmental problems (Kellenberg, 2012). Also, when considering trading waste, social preferences should be take into account, since they play a significant role in the decision to accept waste generated in other areas (Ishimura et al., 2021).

Circular material use rate is calculated as the ratio of material recovered and re-introduced into the economy and total material use. Higher value of this ratio is associated with the reduced environmental impacts of primary material extraction due to larger portion of secondary materials that substitute for primary raw materials.

Competitiveness and innovation area (C4) includes two indicators: private investments, jobs and gross value added related to circular economy sectors (C41), and patents related to recycling and secondary raw materials (C42).

Private investments, jobs and gross value added related to circular economy sectors (C41) comprise investment in assets, number of employees and value added at factor costs in the next sectors: rental and leasing sector, and the recycling sector. As a proxy of this wide-ranging category a value added at factor costs is used.

Patents related to recycling and secondary raw materials (C42) measures the quantity of patents related to recycling and secondary raw materials.

To evaluate the circular economy of the EU countries, a multi-criteria model was created. The hierarchical structure of the model is shown in the Fig. 1.

4. Results and discussion

Based on the above data, firstly a hierarchical cluster analysis was performed in order to determine groups of countries with similar circular economy performance (Table 2).

The results of the cluster analysis indicate a sizeable geographical heterogeneity of the clusters. Concerning the performance of the circular economy of the countries within the cluster, it can be noticed that the best values of the indicators are achieved by the countries within the fourth cluster, while the worst performing are the countries within the first cluster.

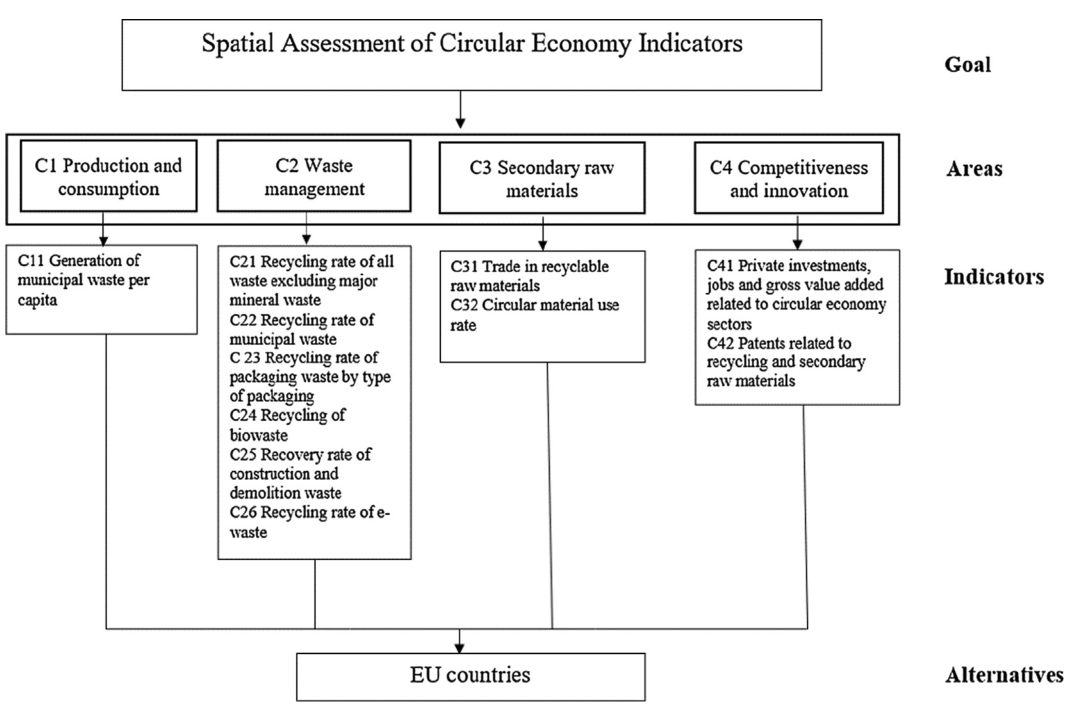

Fig. 1. Hierarchical structure of the model.

Table 2
Cluster analysis of circular economy performance.

Cluster 1	BG, CZ, DE, EE, IE, EL, PL, PT, RO, SI, SK, FI, HR, CY, LV, LT, LU, HU, MT
Cluster 2	DK, AT
Cluster 3	BE, ES, SE
Cluster 4	UK, FR, IT, NL

Source: Authors' calculation.

The further analysis provides the ranking results for 28 European countries according to their performances in areas that contribute circular economy development. This type of research can provide useful information to policy-makers regarding successful circular economy practices and the role of circular economy in sustainable development. The contribution of this paper is reflected in the formulation of a new methodological approach grounded on integration of statistical and multi-criteria methods for countries ranking.

In the first part of the research the PCA was applied. The results of data adequacy check confirm compliance with conditions for factor analysis application (value of Kaiser-Meyer-Olkin Measure of Sampling Adequacy is 0.808). The determination of the number of factors (components) extracted was performed based on following criteria: associated eigenvalues greater than one, at least 60% of cumulative variance explained, and individual contribution to the explanation of the total variance higher than 10%. Giving stated criteria, two components were extracted. After extraction, varimax rotation has been performed, and the rotated loadings estimations represent a base for aggregation of indicators into components, and also, they serve as a basis for weights calculation (Table 3).

The first component has salient loadings on the first seven indicators, while the second component has salient loading on the rest four indicators. Weights of components in created composite indicator are calculated according to the percent of total variance explained by components (Table 4).

Weights have been calculated on re-scaled values of the basic indicators. Consequently, standardized scores of all indicators have an equal range. Consistent with the results concerning the assessment of the significance of particular circular economy areas in the model, the most significant area is waste management (with the calculated weight of 0.691), followed by competitiveness and innovation area (0.181), secondary raw materials area (0.084) and production and consumption area (0.045). The relative importance of criteria undoubtedly demonstrates strategical focus of EU countries on the establishment of the sustainable waste management system. It also stipulates the prime areas that require improvements in order for a country to achieve adequate level of circular economy development. Therefore, it is of utmost importance to improve the efficiency and effectiveness of public services related to waste management, especially given the limited resources available to governments (Managi et al., 2014). The creation of adequate waste management strategies is significant due to the fact that in recent decades there has been a substantial increase in the production of municipal and industrial waste and further increases are expected (Higashida and Managi, 2014). Regardless of the type of waste, waste management essentially contains strategies related to waste reduction, waste treatment and land disposal (Benjamin and Wagner, 2006) and the task of policymakers is to create the most environmentally, economically and socially acceptable combination of waste management strategies.

In the second part of the analysis, creation of composite indicator was conducted using PROMETHEE method where V-shape preference function was selected. The countries rankings are obtained by an overall assessment of performances in four circular economy areas, each containing several indicators, using the appropriate multi-criteria model (Table 5).

According to the results of the analysis, Germany represented the leader in first three biennial periods (2010, 2012, and 2014) based on the analysed indicators of the circular economy. Germany's progress towards a circular economy is evident especially when it comes to municipal waste management. To make a transition towards circular economy, Germany has implemented several well-coordinated initiatives to achieve resource efficiency and recycling goals, with the strengths of Germany's circular economy plan to be found in strong national policies and awareness, as well as the population's receptivity to sustainability issues (Marino and Pariso, 2020). However, in 2016, the Netherlands overtook

Table 4
Weights of indicators within summary index.

Indicator	Weights in Composite indicator
C11	0.045
C21	0.114
C22	0.170
C23	0.127
C24	0.140
C25	0.062
C26	0.078
C31	0.043
C32	0.041
C41	0.090
C42	0.091

Source: Authors' calculation.

Table 3
Factor loading and weights of selected indicators.

	Component 1		Component 2	
	Loadings	Weights of variables within Component 1	Loadings	Weights of variables within Component 2
C11	0.451	0.0957		
C21	0.716	0.1519		
C22	0.875	0.1856		
C23	0.755	0.1603		
C24	0.794	0.1685		
C25	0.530	0.1124		
C26	0.593	0.1257		
C31			0.579	0.2044
C32			0.569	0.2009
C41			0.841	0.2969
C42			0.844	0.2979
Weights of Components in Composite indicator	0.7352		0.2648	

Source: Authors' calculation

Table 5
Ranking of the countries according to the assessed circular economy development in 2010, 2012, 2014 and 2016.

Country	Composite index							
	2010		2012		2014		2016	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank
AT	0.2005	3	0.1726	4	0.1669	4	0.1503	4
BE	0.1721	5	0.1401	6	0.1309	6	0.1474	5
BG	−0.1301	22	−0.1508	24	−0.1228	23	−0.1268	26
HR	−0.227	26	−0.2213	25	−0.1692	25	−0.1114	22
CY	−0.3256	28	−0.2564	28	−0.2331	28	−0.2423	27
CZ	−0.0247	14	−0.0279	15	−0.0347	15	−0.0258	15
DK	0.0984	11	0.0858	11	0.1124	9	0.1009	9
EE	−0.0473	18	−0.068	18	−0.0494	16	−0.1148	25
FI	0.0662	12	0.0419	12	0.0536	12	0.0093	13
FR	0.1865	4	0.1798	3	0.1792	3	0.1647	3
DE	0.2507	1	0.233	1	0.2168	1	0.2028	2
EL	−0.1432	24	−0.2409	26	−0.2174	27	−0.1130	23
HU	−0.0326	16	−0.0662	17	−0.0537	17	−0.0486	18
IE	−0.0858	19	−0.0861	23	−0.0697	19	−0.1110	21
IT	0.1688	6	0.1694	5	0.1522	5	0.1451	6
LV	−0.1107	20	−0.0834	21	−0.1555	24	−0.0642	19
LT	−0.1271	21	−0.0793	20	−0.1063	22	−0.0115	14
LU	0.1243	9	0.1066	9	0.0993	11	0.0778	11
MT	−0.2877	27	−0.2443	27	−0.2169	26	−0.2824	28
NL	0.2226	2	0.2203	2	0.2146	2	0.2127	1
PL	0.0011	13	−0.0142	14	0.0062	13	0.0119	12
PT	−0.0435	17	0.0292	13	−0.0574	18	−0.0341	16
RO	−0.0273	15	−0.0358	16	−0.075	20	−0.104	20
SK	−0.1527	25	−0.0788	19	−0.099	21	−0.1137	24
SI	−0.1304	23	−0.0835	22	−0.0203	14	−0.0431	17
ES	0.1262	8	0.0934	10	0.1187	8	0.1248	7
SE	0.1238	10	0.1259	8	0.1045	10	0.0864	10
UK	0.1542	7	0.1386	7	0.1252	7	0.1129	8

Source: Authors' calculation.

Germany and came in first place according to the analysed indicators of the circular economy. The strategic orientation of the Netherlands towards the circular economy was confirmed in 2016 when the government launched the Circular Economy Program in the Netherlands by 2050 with clearly defined goals, including reducing the use of primary raw materials by 50% by 2030, and striving for the Netherlands economy to be completely circular by 2050 (A Circular Economy in the Netherlands by 2050, 2016).

The results of the study indicate that there are substantial disparities between EU countries regarding the progress towards circular economy (Fig. 2). There is still an obvious difference in the implementation of the circularity from two standpoints. From one standpoint, there is a difference in the circular economy performance between the old and new EU members, where most of the old members are at the top of the list, with the first three places occupied by the EU founding countries: Germany, the Netherlands and France. From another standpoint, the differences between the countries of Northern and Western Europe on the one hand, and the countries of the Southern Europe on the other hand, are evident. Countries such as Cyprus, Greece, Malta and Croatia are at the bottom of the list in terms of their circular economy performance in first three biennial periods, where the last analysed period shows a slight improvement in the circular economy development of Greece and Croatia. The obtained results are consistent with the results revealed by Giannakitsidou et al. (2020), and Škrinjarić (2020).

The obtained results have certain implications. In particular, besides establishing adequate legislation and strategic goals aimed at the transition to a circular economy, especially in countries with the worst performance, it is necessary to establish an adequate system of measuring and monitoring the achievement of defined goals. Also, it is necessary to work on raising the awareness of the population about the importance of achieving circularity, and the importance of preserving the environment. According to Special Eurobarometer 468 (Directorate-General for Communication, 2017), 94% of the EU population say that environmental protection is personally important to them, while 56% of them say that it is very important, but there are significant disparities between Member States in the attitudes of the population. Higher awareness of the importance of the circular economy and the creation of adequate educational profiles, especially in lower-conscious countries, will contribute in two ways: firstly, the population will become more aware and careful in using, reusing and repairing products which will lead to reduction of waste generation and increase recycling rates, and secondly, a better workforce qualified aware of circular economy principles and requirements will lead to faster achievement of circular economy in all types of companies (Škrinjarić, 2020). In addition, there is still work to be done to improve tax legislation. Differences in waste incineration and landfilling tariffs are observed among EU member states, which consequently lead to unstable support to transition towards circular economy, and additionally stimulate the export and import of waste only to evade taxes. Creation of a balanced and stable tax regime in EU for waste incineration and landfilling, in terms of introducing a maximum and minimum tariff for waste incineration and landfilling, could encourage waste prevention and reduction (European Commission, 2020b).

To check the robustness of the result, a sensitivity analysis was performed. Usage of a sensitivity analysis tool offers information regarding possible increases or decreases in criteria weights values that will not change the obtained ranking results (Vivas et al., 2019). Weight stability intervals (Table 6) indicate a relatively low sensitivity of the results to changes in the weights of indicators within the area of competitiveness and innovation, as well as to changes in the weights of certain indicators within the waste management area (such as recovery rate of construction and demoli-

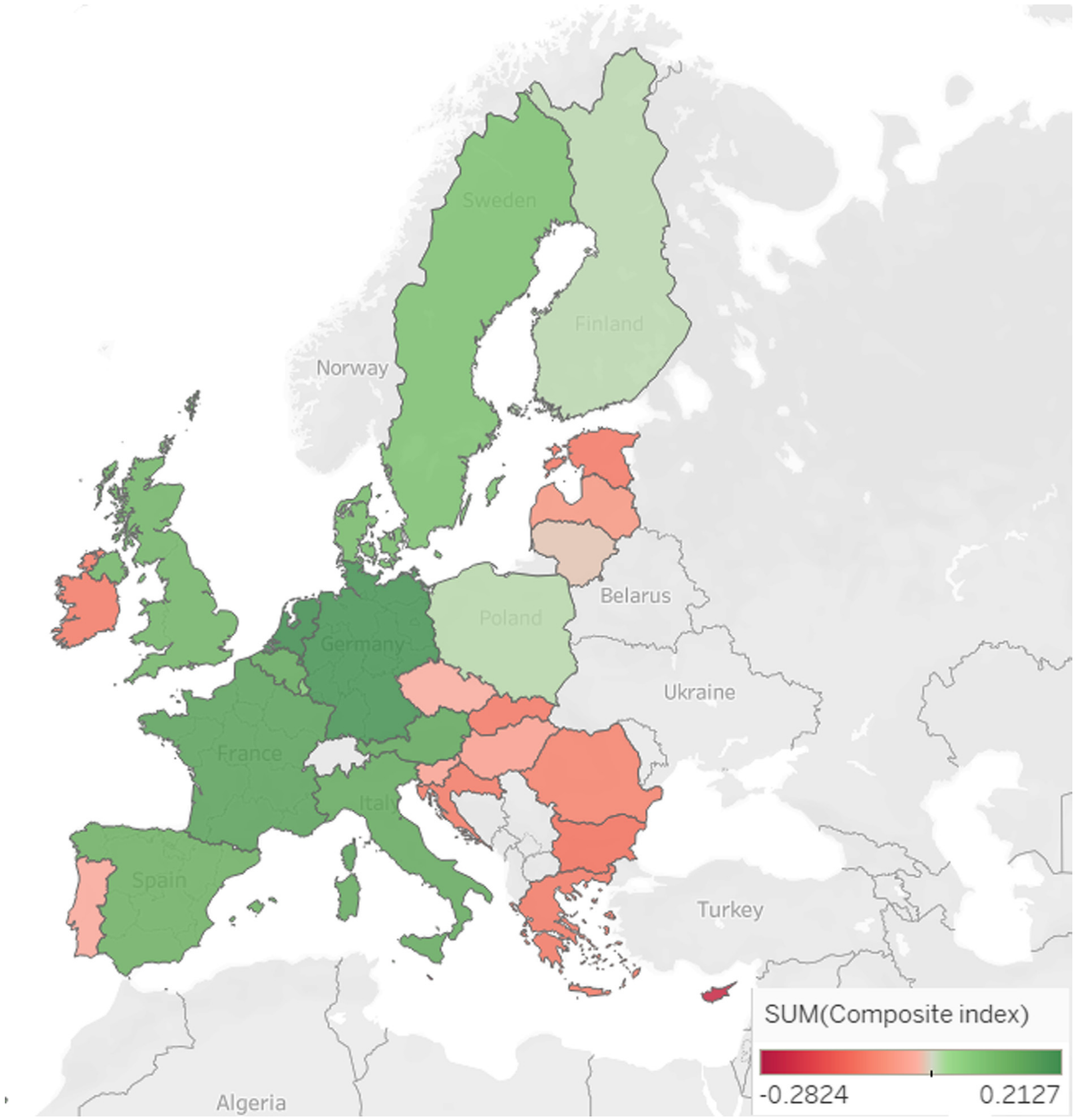

Fig. 2. Preview of the results: circular economy development in the 2016.

Table 6
Sensitivity analysis.

Indicator	Weight	Weight stability interval
C11	0.045	0.0426–0.0454
C21	0.114	0.1105–0.1289
C22	0.170	0.1657–0.1844
C23	0.127	0.1159–0.1747
C24	0.140	0.1392–1.1434
C25	0.062	0.0370–0.0921
C26	0.078	0.0545–0.0858
C31	0.043	0.0423–0.0448
C32	0.041	0.0353–0.0419
C41	0.090	0.0835–0.1039
C42	0.091	0.0881–0.0920

Source: Authors' calculation.

tion waste and recycling rate of e-waste), while the sensitivity of the ranking results to changes in the weight coefficients of the indicators in the other two areas is slightly higher.

Additionally, the analysis of the sensitivity of the results to changes in the choice of the preference function was performed. The results indicate that changes in the preference function lead to a moderate rank reversal, with the most significant rank reversal occurring if the linear preference function is applied (the value of the Spearman's rank correlation coefficient between the ranks obtained using the V-shape preference function and the linear preference function was 0.860), and the lowest rank reversal occurring if the level preference function is applied (the value of the Spearman's rank correlation coefficient between the ranks obtained using the V-shape preference function and the level preference function was 0.978).

Further analysis was dedicated to determining the relationship among the circular economy and socio-economic development on

Table 7
Correlation coefficients.

	EPI2016	EPI2018	EPI2020	HDI2016	HDI2017	HDI2018	HDI2019
Composite index 2016	0.007	0.450*	0.654**	0.602**	0.598**	0.597**	0.599**

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

the one hand, and environmental sustainability on the other hand. To conduct the analysis, data on the Environmental Performance Index (EPI) (Environmental Performance Index, n.d.) and Human Development Index (HDI) (Human Development Index, n.d.) were used.

Based on the value of Spearman's correlation coefficient (Table 7), it can be seen that regarding environmental performance, progress in the circular economy has no immediate impact but the impact is realized subsequently, with the intensity of the relationship increasing with time. On the other hand, when it comes to socio-economic development, the connection between the levels of development of the circular economy and socio-economic development starts instantaneously and remains relatively constant over time. The reason for the positive link between the circular economy development and HDI can be found in the fact that countries with a low level of HDI will give priority to meeting all social needs of their citizens, where the challenge in the context of circularity is reflected in designing a path to inclusive growth which allows development of economy, while remaining within the environmental capacities of the country. On the other hand, countries that have already achieved high levels of satisfaction of their citizen often did that at substantial environmental costs, and confront the immediate necessity to reassess their consumption habits, use resources more efficiently, reduce water and soil pollution and decarbonise their economies (Circle Economy, 2020).

Having in mind the above, it can be concluded that due to the lag in the improvement of environmental performance, it is desirable to start the circular economy development as soon as possible. Also, the development of a circular economy is desirable due to the direct connection with the socio-economic development which will improve the quality of life of people.

5. Conclusion

Environmental pollution caused by increased consumption on the output side can no longer be compensated by improving resource efficiency on the source side, and a more comprehensive approach is needed (Akao and Managi, 2007). The implementation of the circular economy triggers changes in numerous areas, with the main challenge in achieving the circularity being the limited coordination and integration of strategies, policies and decisions of policymakers (Velenturf et al., 2018), which may result in missed opportunities to make progress in circularity (Velenturf et al., 2019), due to inability to monitor progress of the circular economy and provide adequate and timely response. The indisputable significance of the concept of the circular economy raises the question of the existence of adequate metrics for the assessment of countries' progress on the path towards achieving circularity. In recent years, more and more nations have become aware of the need to mitigate environmental degradation, with the transition to a circular economy being considered one of the potential solutions. However, the implementation of appropriate policies is often hindered by the lack of metrics that would allow adequate monitoring of progress towards circularity.

Therefore, this paper offers a model based on statistical and multi-criteria methods for the assessment of circularity at a country level. The level of country's circular economy development is evaluated based on eleven circular economy indicators grouped into following areas: (1) production and consumption, (2) waste management, (3) secondary raw materials, (4) competitiveness and innovation over the period of seven years, with four annual measurements every other year (2010, 2012, 2014 and 2016). Methodology based on combining PCA and PROMETHEE was applied in construction of the composite measure that captures various aspects of circular economy. The idea of the research was that through an objective assessment of the significance of the criteria in the multicriteria model, the exclusion of the compensatory effect (Fusco, 2015) of the significance of individual indicators in the composite index of circular economy development is actually achieved. Therefore, the theoretical contribution of the paper is clearly expressed through the suggested methodology, which improves the existing approaches in measuring the development of the circular economy at the country level.

Empirically, this study contributes to existing knowledge related to the measures of the circular economy by offering a new approach to the assessment of circularity on the example of EU countries. Creating adequate circular economy indicators at the macro level is essential for assessing, controlling and improving circular economy programs and policies, as well as for evaluating their effectiveness (De Pascale et al., 2020). The proposed ranking methodology provides a simple, science-based procedure for tracking progress towards a circularity that allows for evaluation and comparison of countries. The results can provide adequate guidance to policymakers to make strategic decisions aimed at advancing the transition to a circular economy.

Finally, the research determined statistically significant correlation between the development of the circular economy and HDI over a period of four observed successive years. Also, connection was established between the circular economy development and the ecological sustainability of the country, observed through EPI, including 5-year period with three biennial EPI values. Although this is a delayed effect, a statistically significant correlation was determined between the values of the created composite index of the circular economy development and the EPI in 2020.

The limitations of the proposed study are reflected in the lack of up-to-date data, making it unfeasible to analyse recent performance and trends in progress towards a circular economy.

Further analysis in this area can be aimed at identifying the exact reasons for the observed differences between countries by observing specific policies and actions of the circular economy at the country level, as well as further monitoring of the circular economy performance of the over time.

CRediT authorship contribution statement

Jelena J. Stanković: Conceptualization, Methodology, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Supervision; **Vesna Janković-Milić:** Data Curation, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing; **Ivana Marjanović:** Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization; **Jasmina Janjić:** Data Curation, 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.

Acknowledgements

This work was supported by the Ministry of Education, Science and Technological Development of Republic of Serbia under Agreement on the implementation and financing of research and development in 2021 (record number 451-03-68 / 2021-14 / 200100) and within the framework of activities on bilateral cooperation project "Researching capacity for implementation of smart cities as basis for sustainable urban development" (No. 337-00-205/2019-09/36) and "Pametni gradovi u funkciji razvoja nacionalnog gospodarstva" (uniri-drustv-18-255-1424) cunducted by University of Rijeka, Croatia.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2021.04.057.

References

A Circular Economy in the Netherlands by 2050 [WWW Document], 2016. URL https://circulareconomy.europa.eu/platform/sites/default/files/17037circulaireeconomie_en.pdf

Akao, K.-I., Managi, S., 2007. Feasibility and optimality of sustainable growth under materials balance. J. Econ. Dyn. Control 31 (12), 3778–3790. https://doi.org/10.1016/j.jedc.2007.01.013.

Ananda, J., Herath, G., 2009. A critical review of multi-criteria decision making methods with special reference to forest management and planning. Ecol. Econ. 68 (10), 2535–2548. https://doi.org/10.1016/j.ecolecon.2009.05.010.

Andersen, M.S., 2007. An introductory note on the environmental economics of the circular economy. Sustain. Sci. 2 (1), 133–140. https://doi.org/10.1007/s11625-006-0013-6.

Athawale, V.M., Chakraborty, S., 2010. Facility Location Selection using PROMETHEE II Method. Int. Conf. Ind. Eng. Oper. Manag.

Atmaca, E., Basar, H.B., 2012. Evaluation of power plants in Turkey using Analytic Network Process (ANP). Energy 44 (1), 555–563. https://doi.org/10.1016/j.energy.2012.05.046.

Banaitė, D., 2016. Towards Circular Economy : Analysis of Indicators in the context of sustainable development. Soc. Transform. Contemp. Soc.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. 200 (1), 198–215. https://doi.org/10.1016/j.ejor.2009.01.021.

Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., Ignatius, J., 2012. A state-of the-art survey of TOPSIS applications. Expert Syst. Appl. 39 (17), 13051–13069. https://doi.org/10.1016/j.eswa.2012.05.056.

Benjamin, R., Wagner, J., 2006. Reconsidering the law and economics of low-level radioactive waste management. Environ. Econ. Policy Stud. 8 (1), 33–53. https://doi.org/10.1007/BF03353992.

Betrie, G.D., Sadiq, R., Morin, K.A., Tesfamariam, S., 2013. Selection of remedial alternatives for mine sites: A multicriteria decision analysis approach. J. Environ. Manage. 119, 36–46. https://doi.org/10.1016/j.jenvman.2013.01.024.

Bogdanov, O., Jeremić, V., Jednak, S., Čudanov, M., 2019. Scrutinizing the smart city index: A multivariate statistical approach*. Zb. Rad. Ekon. Fak. au Rijeci. https://doi.org/10.18045/zbefri.2019.2.777

Brans, J.-P., Mareschal, B., 2005. Chapter 5 PROMETHEE METHODS. Mult. Criteria Decis. Anal. State Art Surv.

Brans, J.P., 1982. L'ingenierie de la decision; Elaboration d'instruments d'aide a la decision. La methode PROMETHEE., in: L'aide a La Decision: Nature, Instruments et Perspectives d'Avenir.

Brans, J.P., Vincke, P.h., 1985. Note—A Preference Ranking Organisation Method. Manage. Sci. 31 (6), 647–656. https://doi.org/10.1287/mnsc.31.6.647.

Brans, J.P., Vincke, P.h., Mareschal, B., 1986. How to select and how to rank projects: The Promethee method. Eur. J. Oper. Res. 24 (2), 228–238. https://doi.org/10.1016/0377-2217(86)90044-5.

Calisto Friant, M., Vermeulen, W.J.V., Salomone, R., 2021. Analysing European Union circular economy policies: words versus actions. Sustain. Prod. Consum. 27, 337–353. https://doi.org/10.1016/j.spc.2020.11.001.

Carrizosa, E., Conde, E., Pascual, A., Romero-Morales, D., 1997. Closest Solutions in Ideal-Point Methods. https://doi.org/10.1007/978-3-642-46854-4_30

Circle Economy, 2020. The Circularity Gap Report 2020 [WWW Document]. URL circularity-gap.world (accessed 1.28.21).

Competence Centre on Composite Indicators and Scoreboards, 2020. 10 Step Guide [WWW Document]. Eur. Comm. Sci. Knowl. Serv. URL https://ec.europa.eu/jrc/en/coin/10-step-guide/step-6

Corona, B., Shen, L.i., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498.

Dantsis, T., Douma, C., Giourga, C., Loumou, A., Polychronaki, E.A., 2010. A methodological approach to assess and compare the sustainability level of agricultural plant production systems. Ecol. Indic. 10 (2), 256–263. https://doi.org/10.1016/j.ecolind.2009.05.007.

de Brito, M.M., Evers, M., 2015. Review Article: Multi-criteria decision making for flood risk management: a survey of the current state-of-the-art. Nat. Hazards Earth Syst. Sci. Discuss. https://doi.org/10.5194/nhessd-3-6689-2015

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2020. A systematic review for measuring circular economy: The 61 indicators. J. Clean. Prod. 281, 124942. https://doi.org/10.1016/j.jclepro.2020.124942.

Directorate-General for Communication, 2017. Special Eurobarometer 468 [WWW Document]. URL https://data.europa.eu/euodp/en/data/dataset/S2156_88_1_468_ENG

EASAC, 2016. Priorities for critical materials for a circular economy, European Academies Science Advisory Council.

EEA, 2016. Circular economy in Europe - developing the knowledge base, European Environmental Agency.

El Emam, K., Goldenson, D., McCurley, J., Herbsleb, J.D., 1998. Success or Failure? Modeling the Likelihood of Software Process Improvement. International Software Engineering Research Network Technical Report ISERN-98-15, Source

Ellen, M., Company, M.&, 2014. Towards the Circular Economy: Accelerating the scale-up across global supply chains, World Economic Forum.

Environmental Performance Index, n.d. Environmental Performance Index [WWW Document]. URL https://epi.yale.edu/

European Commission, 2020a. First Circular Economy Strategy - Environment - European Commission [WWW Document]. URL https://ec.europa.eu/environment/circular-economy/first_circular_economy_action_plan.html

European Commission, 2020b. Products and Circular Economy. Policy recommendations derived from Research & Innovation projects. https://doi.org/10.2777/15587

European Environment Agency, 2020. Generation of waste excluding major mineral wastes [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/daviz/generation-of-waste-excluding-major-3#tab-dashboard-01 (accessed 12.2.20).

[dataset] Eurostat, 2020a. Main tables - Eurostat [WWW Document]. URL https://ec.europa.eu/eurostat/web/circular-economy/indicators/main-tables (accessed 12.2.20).

Eurostat, 2020b. Municipal waste statistics - Statistics Explained [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics (accessed 12.2.20).

Eurostat, 2020c. Recycling rate of all waste excluding major mineral waste [WWW Document]. URL https://ec.europa.eu/eurostat/web/products-datasets/product?code=cei_wm010 (accessed 12.2.20).

Franklin-Johnson, Elizabeth, Figge, Frank, Canning, Louise, 2016. Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023.

Freudenberg, M., 2003. Composite Indicators of Country Performance: A Critical Assessment (No. 2013/16). https://doi.org/10.1787/405566708255

Frini, Anissa, Ben Amor, Sarah, 2019. MUPOM: A multi-criteria multi-period outranking method for decision-making in sustainable development context. Environ. Impact Assess. Rev. 76, 10–25. https://doi.org/10.1016/j.eiar.2018.11.002.

Frini, Anissa, Benamor, Sarah, 2018. Making decisions in a sustainable development context: a state-of-the-art survey and proposal of a multi-period single synthesizing criterion approach. Comput. Econ. 52 (2), 341–385. https://doi.org/10.1007/s10614-017-9677-5.

Fusco, Elisa, 2015. Enhancing non-compensatory composite indicators: A directional proposal. Eur. J. Oper. Res. 242 (2), 620–630. https://doi.org/10.1016/j.ejor.2014.10.017.

Geng, Yong, Fu, Jia, Sarkis, Joseph, Xue, Bing, 2012. Towards a national circular economy indicator system in China: An evaluation and critical analysis. J. Clean. Prod. 23 (1), 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339 (6127), 1526–1527. https://doi.org/10.1126/science:1227059.

Giamalaki, Marina, Tsoutsos, Theocharis, 2019. Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach. Renew. Energy. 141, 64–75. https://doi.org/10.1016/j.renene.2019.03.100.

Giannakitsidou, Olga, Giannikos, Ioannis, Chondrou, Anastasia, 2020. Ranking European countries on the basis of their environmental and circular economy performance: A DEA application in MSW. Waste Manag 109, 181–191. https://doi.org/10.1016/j.wasman.2020.04.055.

Goodland, R, 1995. The concept of environmental sustainability. Annu. Rev. Ecol. Syst. 26 (1), 1–24. https://doi.org/10.1146/annurev.es.26.110195.000245.

Govender, P., Sivakumar, V., 2020. Application of k-means and hierarchical clustering techniques for analysis of air pollution: A review (1980–2019). Atmos. Pollut. Res. 11 (1), 40–56. https://doi.org/10.1016/j.apr.2019.09.009.

Govindan, Kannan, Jepsen, Martin Brandt, 2016. ELECTRE: A comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. 250 (1), 1–29. https://doi.org/10.1016/j.ejor.2015.07.019.

Greco, Salvatore, Ishizaka, Alessio, Tasiou, Menelaos, Torrisi, Gianpiero, 2019. On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness. Soc. Indic. Res. 141 (1), 61–94. https://doi.org/10.1007/s11205-017-1832-9.
Gul, Muhammet, Celik, Erkan, Aydin, Nezir, Taskin Gumus, Alev, Guneri, Ali Fuat, 2016. A state of the art literature review of VIKOR and its fuzzy extensions on applications. Appl. Soft Comput. J. 46, 60–89. https://doi.org/10.1016/j.asoc.2016.04.040.
Hajkowicz, Stefan, Collins, Kerry, 2007. A review of multiple criteria analysis for water resource planning and management. Water Resour. Manag. 21 (9), 1553–1566. https://doi.org/10.1007/s11269-006-9112-5.
Health Organization Regional Office for Europe, W., 2015. Glossary of Life-course Terms [WWW Document]. URL http://www.euro.who.int/__data/assets/pdf_file/0009/289539/Glossary-Life-course-Terms.pdf
Higashida, Keisaku, Managi, Shunsuke, 2014. Determinants of trade in recyclable wastes: Evidence from commodity-based trade of waste and scrap. Environ. Dev. Econ. 19 (2), 250–270. https://doi.org/10.1017/S1355770X13000533.
Human Development Index, n.d. Human Development Index [WWW Document]. URL http://www.hdr.undp.org/
Huysman, Sofie, De Schaepmeester, Jonas, Ragaert, Kim, Dewulf, Jo, De Meester, Steven, 2017. Performance indicators for a circular economy: A case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54. https://doi.org/10.1016/j.resconrec.2017.01.013.
Ishimura, Yuichi, Takeuchi, Kenji, Carlsson, Fredrik, 2021. Why do municipalities accept disaster waste? Evidence from the great east Japan earthquake. Environ. Econ. Policy Stud. 23 (2), 275–308. https://doi.org/10.1007/s10018-020-00297-0.
Ishizaka, A., Nemery, P., 2013. Multi-Criteria Decision Analysis: Methods and Software, Multi-Criteria Decision Analysis: Methods and Software. https://doi.org/10.1002/9781118644898
Jafarzadegan, M., Safi-Esfahani, F., Beheshti, Z., 2019. Combining hierarchical clustering approaches using the PCA method. Expert Syst. Appl. 137, 1–10. https://doi.org/10.1016/j.eswa.2019.06.064.
Janik, Agnieszka, Ryszko, Adam, 2019. Circular economy in companies: an analysis of selected indicators from a managerial perspective. Multidiscip. Asp. Prod. Eng. 2 (1), 523–535. https://doi.org/10.2478/mape-2019-0053.
Jia, C.R., Zhang, J., 2011. Evaluation of regional circular economy based on matter element analysis, in: Procedia Environmental Sciences. https://doi.org/10.1016/j.proenv.2011.12.099
Kabir, Golam, Sumi, Razia Sultana, 2014. Integrating fuzzy analytic hierarchy process with PROMETHEE method for total quality management consultant selection. Prod. Manuf. Res. 2 (1), 380–399. https://doi.org/10.1080/21693277.2014.895689.
Kellenberg, Derek, 2012. Trading wastes. J. Environ. Econ. Manage. 64 (1), 68–87. https://doi.org/10.1016/j.jeem.2012.02.003.
Khalili, Nasrin R., Duecker, Susanna, 2013. Application of multi-criteria decision analysis in design of sustainable environmental management system framework. J. Clean. Prod. 47, 188–198. https://doi.org/10.1016/j.jclepro.2012.10.044.
Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular Economy: The Concept and its Limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.
Kristensen, Heidi Simone, Mosgaard, Mette Alberg, 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability?. J. Clean. Prod. 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531.
Kumar, N., 2019. The Professionals Point: Advantages and Disadvantages of Principal Component Analysis in Machine Learning [WWW Document]. URL http://theprofessionalspoint.blogspot.com/2019/03/advantages-and-disadvantages-of_4.html (accessed 4.15.21).
Kurita, K., Managi, S., 2021. Circular economy in cities: An economic theory to decouple economic development from waste (No. 105533).
Lam, Jasmine Siu Lee, Lai, Kee-hung, 2015. Developing environmental sustainability by ANP-QFD approach: The case of shipping operations. J. Clean. Prod. 105, 275–284. https://doi.org/10.1016/j.jclepro.2014.09.070.
Lavoie, Roxane, Deslandes, Julie, Proulx, François, 2016. Assessing the ecological value of wetlands using the MACBETH approach in Quebec City. J. Nat. Conserv. 30, 67–75. https://doi.org/10.1016/j.jnc.2016.01.007.
Li, R.H., Su, C.H., 2012. Evaluation of the circular economy development level of Chinese chemical enterprises. Procedia Environ. Sci. 13, 1595–1601. https://doi.org/10.1016/j.proenv.2012.01.151.
Li, Shulin, 2012. The research on quantitative evaluation of circular economy based on waste input-output analysis. Procedia Environ. Sci. 12, 65–71. https://doi.org/10.1016/j.proenv.2012.01.248.
Lolli, Francesco, Balugani, Elia, Ishizaka, Alessio, Gamberini, Rita, Butturi, Maria Angela, Marinello, Samuele, Rimini, Bianca, 2019. On the elicitation of criteria weights in PROMETHEE-based ranking methods for a mobile application. Expert Syst. Appl. 120, 217–227. https://doi.org/10.1016/j.eswa.2018.11.030.
Lolli, Francesco, Ishizaka, Alessio, Gamberini, Rita, Rimini, Bianca, Ferrari, Anna Maria, Marinelli, Simona, Savazza, Roberto, 2016. Waste treatment: an environmental, economic and social analysis with a new group fuzzy PROMETHEE approach. Clean Technol. Environ. Policy. 18 (5), 1317–1332. https://doi.org/10.1007/s10098-015-1087-6.
Mahdiyar, A., Tabatabaee, S., Durdyev, S., Ismail, S., Abdullah, A., Wan Mohd Rani, W. N.M., 2019. A prototype decision support system for green roof type selection: A cybernetic fuzzy ANP method. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2019.101532
Managi, Shunsuke, Hibiki, Akira, Shimane, Tetsuya, 2014. Efficiency or technology adoption: A case study in waste-treatment technology. Resour. Energy Econ. 36 (2), 586–600. https://doi.org/10.1016/j.reseneeco.2013.09.002.
Marino, Alfonso, Pariso, Paolo, 2020. Comparing European countries' performances in the transition towards the Circular Economy. Sci. Total Environ. 729, 138142. https://doi.org/10.1016/j.scitotenv.2020.138142.
Mayer, Andreas, Haas, Willi, Wiedenhofer, Dominik, Krausmann, Fridolin, Nuss, Philip, Blengini, Gian Andrea, 2019. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. J. Ind. Ecol. 23 (1), 62–76. https://doi.org/10.1111/jiec.12809.
Moraga, Gustavo, Huysveld, Sophie, Mathieux, Fabrice, Blengini, Gian Andrea, Alaerts, Luc, Van Acker, Karel, de Meester, Steven, Dewulf, Jo, 2019. Circular economy indicators: What do they measure?. Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.
Nicoletti, G., Scarpetta, S., Boylaud, O., 2005. Summary indicators of product market regulation with an extension to employment protection legislation. SSRN Electron. J. https://doi.org/10.2139/ssrn.201668.
Oberschmidt, Julia, Geldermann, Jutta, Ludwig, Jens, Schmehl, Meike, 2010. Modified PROMETHEE approach for assessing energy technologies. Int. J. Energy Sect. Manag. 4 (2), 183–212. https://doi.org/10.1108/17506221011058696.
OECD, 2020. Waste - Municipal waste - OECD Data [WWW Document]. URL https://data.oecd.org/waste/municipal-waste.htm (accessed 12.2.20).
Parchomenko, Alexej, Nelen, Dirk, Gillabel, Jeroen, Rechberger, Helmut, 2019. Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics. J. Clean. Prod. 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357.
Pauliuk, Stefan, 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019.
Pearce, D.W. and R.K.T., 1990. Economics of Natural Resources and the Environment. Harvester Wheatsheaf, Hemel Hempstead.
Penadés-Plà, Vicent, García-Segura, Tatiana, Martí, José, Yepes, Víctor, 2016. A review of multi-criteria decision-making methods applied to the sustainable bridge design. Sustain 8 (12), 1295. https://doi.org/10.3390/su8121295.
Punj, Girish, Stewart, David W., 1983. Cluster analysis in marketing research: review and suggestions for application. J. Mark. Res. 20 (2), 134. https://doi.org/10.2307/3151680.
Ranđelović, D., Stanković, Jelena, Janković-Milić, V., Stanković, Jovica, 2013. Weight coefficents determination based on parameters in factor analysis. Metal. Int. 18, 128–131.
Ranđelović, Milan, Stanković, Jelena, Kuk, Kristijan, Savić, Gordana, Ranđelović, Dragan, 2018. An approach to determining the importance of model criteria in certifying a city as business-friendly. Interfaces (Providence). 48 (2), 156–165. https://doi.org/10.1287/inte.2017.0923.
Rogers, Peter, Daly, Herman E., 1996. Beyond growth: the economics of sustainable development. Popul. Dev. Rev. 22 (4), 783. https://doi.org/10.2307/2137812.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling. https://doi.org/10.3390/recycling2010006
Saisana, M., Tarantola, S., 2002. State-of-the-art Report on Current Methodologies and Practices for Composite Indicator Development, Joint Research Centre. Italy: European Commission.
Sarrazin, R., De Smet, Y., Rosenfeld, J., 2018. An extension of PROMETHEE to interval clustering. Omega (United Kingdom) 80, 12–21. https://doi.org/10.1016/j.omega.2017.09.001.
Sassanelli, Claudio, Rosa, Paolo, Rocca, Roberto, Terzi, Sergio, 2019. Circular economy performance assessment methods: A systematic literature review. J. Clean. Prod. 229, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019.
Simsek, Yeliz, Watts, David, Escobar, Rodrigo, 2018. Sustainability evaluation of Concentrated Solar Power (CSP) projects under Clean Development Mechanism (CDM) by using Multi Criteria Decision Method (MCDM). Renew. Sustain. Energy Rev. 93, 421–438. https://doi.org/10.1016/j.rser.2018.04.090.
Škrinjarić, Tihana, 2020. Empirical assessment of the circular economy of selected European countries. J. Clean. Prod. 255, 120246. https://doi.org/10.1016/j.jclepro.2020.120246.
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: Moving from rhetoric to implementation. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2012.11.020.
Tabachnick, B.G., Fidell, L.S., 2012. Using multivariate statistics. Harper and Row, New York.
Ünal, E., Shao, J., 2018. A taxonomy of circular economy implementation strategies for manufacturing firms: Analysis of 391 cradle-to-cradle products. https://doi.org/10.1016/j.jclepro.2018.11.291
Velasquez, M., Hester, P., 2013. An analysis of multi-criteria decision making methods. Int. J. Oper. Res.
Velenturf, Anne P.M., Archer, Sophie A., Gomes, Helena I., Christgen, Beate, Lag-Brotons, Alfonso J., Purnell, Phil, 2019. Circular economy and the matter of integrated resources. Sci. Total Environ. 689, 963–969. https://doi.org/10.1016/j.scitotenv.2019.06.449.
Velenturf, Anne, Purnell, Phil, Tregent, Mike, Ferguson, John, Holmes, Alan, 2018. Co-producing a vision and approach for the transition towards a circular

economy: Perspectives from government partners. Sustain 10 (5), 1401. https://doi.org/10.3390/su10051401.
Vivas, Renato, Sant'anna, Ângelo, Esquerre, Karla, Freires, Francisco, 2019. Measuring sustainability performance with multi criteria model: a case study. Sustainability 11 (21), 6113. https://doi.org/10.3390/su11216113.
Wang, Heming, Schandl, Heinz, Wang, Xinzhe, Ma, Fengmei, Yue, Qiang, Wang, Guoqiang, Wang, Yao, Wei, Yao, Zhang, Zhihe, Zheng, Ruiying, 2020. Measuring progress of China's circular economy. Resour. Conserv. Recycl. 163, 105070. https://doi.org/10.1016/j.resconrec.2020.105070.
World Commission on Environment and Development, 2017. Brundtland Report - Our common future. Our Common Futur.
Xu, Pengpeng, Chan, Edwin H.W., Visscher, Henk J., Zhang, Xiaoling, Wu, Zezhou, 2015. Sustainable building energy efficiency retrofit for hotel buildings using EPC mechanism in China: Analytic Network Process (ANP) approach. J. Clean. Prod. 107, 378–388. https://doi.org/10.1016/j.jclepro.2014.12.101.
Yang, Q., Chen, M., Gao, Q., 2011. Research on the circular economy in West China, in: Energy Procedia. https://doi.org/10.1016/j.egypro.2011.03.246