International Journal of Environment and Sustainable Development

ISSN online: 1478-7466 - ISSN print: 1474-6778
https://www.inderscience.com/ijesd

The circular economy for sustainable development: implementation strategies in advanced small open economies

Lina Dagilienė, Jurgita Bruneckienė, Viktorija Varaniūtė, Mantas Lukauskas

DOI: 10.1504/IJESD.2021.10040657

Article History:

Received:	25 January 2021
Accepted:	25 May 2021
Published online:	05 December 2022

The circular economy for sustainable development: implementation strategies in advanced small open economies

Lina Dagilienė, Jurgita Bruneckienė and Viktorija Varaniūtė*

School of Economics and Business,
Kaunas University of Technology,
Gedimino St. 50, LT-44239, Kaunas, Lithuania
Email: lina.dagiliene@ktu.lt
Email: jurgita.bruneckiene@ktu.lt
Email: viktorija.varaniute@ktu.lt
*Corresponding author

Mantas Lukauskas

Faculty of Mathematics and Natural Sciences,
Kaunas University of Technology,
Studentų str. 50, LT-51368, Kaunas, Lithuania
Email: mantas.lukauskas@ktu.lt

Abstract: Sustainable development and circular economy (CE) policy perspectives are growing in importance. However, there is little empirical research about the implementation of a CE or a critical review of its indicators at the country level. Using an institutional approach, this paper explores CE implementation strategies in advanced small open economies (SOEs) in the European Union (EU). We used a principal components analysis (PCA) and a clustering analysis based on data from the EU monitoring framework for the CE, specifically 13 small open economies from 2010–2017. The main findings reveal three CE implementation strategies correlated with CE development stages: integrated to value chain, focused on institutional compliance and fragmented profiles. Surprisingly, we found no evidence for the expansion of CE-related sectors based upon persons employed, value added or gross investments. This topic deserves further investigation, with important implications for future research and policymaking.

Keywords: circular economy; CE; strategy; small open economy; SOEs; implementation; principal components analysis; PCA; indicators.

Reference to this paper should be made as follows: Dagilienė, L., Bruneckienė, J., Varaniūtė, V. and Lukauskas, M. (2023) 'The circular economy for sustainable development: implementation strategies in advanced small open economies', *Int. J. Environment and Sustainable Development*, Vol. 22, No. 1, pp.51–76.

Biographical notes: Lina Dagilienė is a Professor and Principal Investigator of Digitalization Research Group at School of Economics and Business, Kaunas University of Technology. She is the Leader of CEMESOE Project group that investigates macroeconomic effects in a small open economy by moving from a

linear economic model to a circular economy. She has extensive experience in the participation in and leadership of research and educational projects (Horizon 2020, Lithuanian Research Council, DAAD, Erasmus+). Her current research interests focus on interdisciplinary economic topics, in particular corporate sustainability, circular business models, sustainability and environmental reporting, data analytics.

Jurgita Bruneckienė is a Professor and researcher of Sustainable Economics Research Group at the School of Economics and Business, Kaunas University of Technology. She is a member of research projects whose topics are focused on the circular economy, its development and implementation. Current research interests focus on circular economy, competitiveness of countries and regions, smart economic development, and economic resilience.

Viktorija Varaniūtė is an Associate Professor and researcher of Digitalization Research Group at the School of Economics and Business, Kaunas University of Technology, Lithuania. She is a member of research projects whose topics are focused on the circular economy, its development and implementation. Her current research interests are related to the research on interdisciplinary topics such as circular business models, sustainable development, value measurement and digital transformation.

Mantas Lukauskas is a doctoral student at the Kaunas University of Technology, Faculty of Mathematics and Natural Sciences and a researcher at Zyro. He carries out various projects in which he performs the functions of a data researcher. His main areas of interest are applying mathematical and statistical models and developing artificial intelligence models (classification models, clustering models, NLP, etc.) and programming (Python and R).

1 Introduction

In recent years, the prevailing view in the economic literature has been that sustainability must come at the price of economic growth (WEF, 2019). Although the circular economy (CE) is a contested concept (Korhonen et al., 2018), it is often presented as a practical strategy for implementing sustainable development. To date, a wide variety of CE-related research has been published worldwide. The majority of papers on CE focus on resource scarcity and efficiency, followed by waste reduction and recycling (Ghisellini et al., 2016; Kirchherr et al., 2018), increasing resource productivity and decoupling resource utilisation from economic growth (D'Amato et al., 2017) at different aggregation levels as well as identifying Covid-19 implications for sustainable development (Alvarez-Risco et at., 2021). Overall, the system level (Moraga et al., 2019; D'Amato et al., 2017; Davies and Hall, 2006) and inter-organisational approach (Korhonen et al., 2018; Kirchherr et al., 2017) are emphasised strongly by identifying several perspectives of implementation: micro (Kirchherr et al., 2018; Seth et al., 2018), meso (Baldassarre et al., 2019; Santagata et al., 2020) and macro (Geerken et al., 2019; Mayer et al., 2018; OECD, 2017; Parchomenko et al., 2019).

However, a limited number of studies address issues of countries' CE implementation and indicators: energy and environmental efficiency (Mavi and Mavi, 2019), the assessment of environmental and circular economy performance (Giannakitsidou et al., 2020; Marino and Pariso, 2020; Škrinjarić, 2020) and conceptual insights about measuring CE (Moraga et al., 2019). Indicators are being developed both to provide evidence in support of CE policies and to monitor progress. The monitoring of CE at a macro scale currently includes methods using material flow, energy and input-output analysis (Moraga et al., 2019), focusing on resource efficiency and waste management. On the other hand, there are contradictions in implementing CE on a large scale, which relates mainly to its viability and biophysical feasibility in a given socio-economic system (Giampietro et al., 2019). Moreover, the large-scale recycling of materials may slow the economic process (Giampietro et al., 2019) because, currently, neither the global economy nor the economies of developed countries are circular (Haas et al., 2015).

The empirical focus of this paper is on advanced small open economies (SOEs) in the EU. In 2018, the EU monitoring framework on CE progress was created. To date, analyses primarily centre on large economies: China, the United States, Italy, Germany and the United Kingdom. Large economies have done a lot supporting CE-related industries and concerning CE in their roadmaps. In comparison, smaller countries have a tradition of collaborating because they are smaller and more agile. Geerken et al. (2019) emphasise that more competitive CE sectors in an open economy can benefit from new CE activities domestically or abroad. Within this context, advanced small open economies in the EU offer an interesting case to investigate CE implementation. Specifically, EU directives must be applicable at the same scale for all countries, and the local context and domestic market are essential in fostering circularity. Compared with large countries, SOEs usually are exporters and might face challenges in closing the loop. Therefore, this study poses the following research question: How do SOEs implement a CE?

Taking into consideration the given trade-offs and the scant research into countries' historical empirical data concerning CE implementation, this research explores how CE monitoring indicators could be used to identify CE implementation strategies. The institutional approach justifies the empirical application of the EU monitoring framework for the circular economy. We applied a principal components analysis (PCA) to identify CE strategies in SOEs because it is useful for exploratory data analysis and better visualises the variation presented in a multivariable dataset. Subsequently, a cluster analysis was used to indicate the homogeneity of CE strategies among different SOEs.

This paper makes several significant contributions. Firstly, it contributes to the economic development literature by exploring the concept of CE across macro, meso and micro levels and using CE indicators to monitor countries' progress. Secondly, the focus has been placed on SOEs because CE has been explored more in companies, industries and large economies. Finally, the paper provides original empirical evidence of CE implementation strategies in advanced SOEs.

The paper is structured in the following manner. First, it analyses the literature on CE policies and CE indicators, focusing on advanced SOEs. Then, the research methodology is introduced. The subsequent section presents the key findings, and the paper concludes with a discussion of the results, study limitations and directions for further research.

2 Theoretical background

2.1 Circular economy: policy

The World Economic Forum (WEF), which has been measuring countries' economic competitiveness since 1979, defines competitiveness as: 'the set of institutions, policies and factors that determine the level of productivity of a country'. Today the competitiveness of a country results from the entrepreneurial activity of individual firms and appropriate institutional policies. More importantly, most countries obtain different results concerning social and environmental factors at the same level of competitiveness (WEF, 2019). For example, on the environmental front, while Sweden and the United States both score above 80/100 on competitiveness, Sweden increased its reliance on renewable energy by 13% over the past 15 years, while the USA did so by only 3%.

An exceptional feature of CE is that it has primarily emerged from legislation (Davies and Hall, 2006; Murray et al., 2017; Parchomenko et al., 2019), as exemplified by the cases of China, Japan and the EU. Murray et al. (2017) notes the development of CE implementation since 1973, when the first National Environmental Protection Conference formulated environmental protection policies and guidelines. China is one of the first countries to implement a national CE strategy; as a result, there is extensive research material on this case (Geng et al., 2012; Homrich et al., 2018). It should be noted that CE was primarily an industrial ecology agenda to examine how the waste of one company could become a resource for another. However, more recent CE policies look at eco-design, extended producer responsibilities and means of reducing, reusing and recycling activities in manufacturing, circulation and consumption (EC, 2020).

Table 1 Trade-offs across different levels of CE implementation

CE	*Implementation*	
	Short term	*Long term*
Micro level (company)	High upfront investment costs and higher prices for products (Kirchherr et al., 2018; Seth et al., 2018)	No trade-offs: reduce waste, optimise resources and costs (Lieder and Rashid)
Meso level (industry, city)	No trade-offs: benefits from the by-products across the supply chain (Lieder and Rashid)	No trade-offs: rise of new CE sectors and job creation (Geerken et al., 2019; OECD, 2017)
Macro level (region, country)	Possible trade-offs: large scale recycling (Giampietro et al., 2019)	Rise of new CE sectors and job creation (EC, 2015; OECD, 2017)

Nevertheless, the orientation towards greater resource efficiency derives from a scarcity of natural resources and land. For example, the EU economy depends on raw materials from the rest of the world. More than 60% of the EU's total physical imports are raw products (EC, 2019). In reconciling economic growth with environmental benefits by moving to regeneration and restoration rather than extraction and consumption, the European Commission has recognised the urgency of moving towards CE and, in 2015, adopted the Circular Economy Package and an action plan. At the national level, Member States identified priorities related to CE in their smart specialisation strategies. The EU CE policy platform's construction has evolved from waste management policies, i.e., the first EU Packaging Directive in 1994, the End-of-Life Vehicles Directive in the late

1990s and the 2008 Waste Framework Directive. Public policies remain crucial in driving the EU towards full CE implementation (Cainelli et al., 2020).

Strategic institutional requirements for the implementation of a CE package are being developed, in which the targeted indicators for reducing the amount of waste and the negative environmental impact were set forth for each Member State in 2018 (EC, 2018a). At the EU level, CE policy includes actions throughout the value chain (Geerken et al., 2019) and aims to measure its contribution to at least four areas: production and consumption, waste management, secondary raw materials and competitiveness and innovation. According to the estimations of the Ellen MacArthur Foundation (EMAF) and the McKinsey Institute (2015), applying CE principles in all sectors and industries will benefit the EU environmentally and socially. It will additionally have the potential to generate a net economic benefit of EUR 1.8 trillion by 2030.

However, CE is a new policy in the EU, which means that Member States have diverse implementation levels. Therefore, we apply a systems perspective (Kirchherr et al., 2017) to present a theoretical discussion on the trade-offs of implementing CE (Table 1).

2.2 Circular economy: indicators

In scientific publications and studies focused on CE indicators, one can notice the prevalence of studies that explore indicators to assess CE implementation at different levels. From the microsystems perspective, a particular company or industry, by reducing waste and optimising resources for cleaner production, may lessen its environmental footprint (Lieder and Rashid, 2016) and optimise its cost structure in the long run. In addition, CE may increase costs and accordingly raise the prices of products, reducing the competitiveness of a company's product. However, high upfront investment costs (Kirchherr et al., 2018; Seth et al., 2018) usually appear when first implementing changes towards cleaner production or circular design. By measuring corporate CE strategies, Elia et al. (2017) proposes a taxonomy of environmental indicators split into material and energy flows, land use and consumption and other life cycle-based assessments.

Lieder and Rashid (2016) further detail the micro level by splitting it into the factory (cleaner production) and inter-organisational levels, which already verges on the meso level. The mesosystems perspective looks at interactions among different companies or industries where each benefit from the by-products of one industry as raw resources for production, which is analogous to ecological industry concepts. The sectors with great potential in CE are repair, waste and recycling; rental and leasing; secondary material production, repair and remanufacture; the service sector; and the sharing economy (OECD, 2017). Therefore, more competitive CE-relevant sectors in an open economy can benefit from new CE activities, domestically or abroad (Geerken et al., 2019).

Overall, governmental decisions are crucial in implementing CE, as engineering and technological barriers do not stop the transition to CE (Kirchherr et al., 2018). Over the last ten years, there has been much improvement regarding renewable energy technologies and eco-design. Technical limitations and the continuous increase in demand might explain why fossil fuels still account for ~80% of total energy consumption (WEF, 2019). In addition, at the meso level, the role of cities is critical when implementing CE. About 85% of EU GDP is generated in cities (EC, 2019).

Therefore, it is not surprising that the most impactful cities consider the principles of CE in their public strategic documents and need innovative measurement tools. Relatedly, Santagata et al. (2020) explore circular indicators for urban areas, which include the following characteristics: network-based, integrative, multi-criteria, preventive eco-design, regenerative and redistributive.

The macrosystems perspective highlights the need to adjust the industrial composition and structure of the entire economy (Kirchherr et al., 2017). CE might be seen as an alternative, more sustainable flow model for an economic system, one that is cyclical and regenerative (EMAF and McKinsey Institute, 2015; Korhonen et al., 2018). Mayer et al. (2018) explore the progress to CE on an economy-wide scale, examining whether absolute reductions in resource use and waste flows were achieved. The authors propose a comprehensive biophysical assessment of CE, linked to official statistics on resource extraction and use and waste flows in a mass balanced approach. CE is mainly a strategy for economic growth (Giampietro et al., 2019), and the wider benefits of CE include the creation of new competitive advantages (EC, 2019).

When it comes to the macro level, some trade-offs regarding inputs, primary flows and circularity might arise. Economic activity is entropic and cannot be circular. According to Giampietro et al. (2019), primary flows—including water, energy and food—cannot be produced by the economic system but depend on eco-system inputs. Moreover, these flows, essential to provide a life-support system to the economic process, are orders of magnitude larger than those under human control. Thus, the lack of circularity of energy and food cannot be solved through technological innovation. Energy and food flows are degraded through use, and the process is irreversible: one cannot undigest food or unburn fuels.

The other problem is that in most European, American and Asian cases, the focus is on waste recycling rather than turning waste into new materials or products (Ghisellini et al., 2016). The EU economy is not circular and has not become more circular in the last decade, nor is the global economy or the economies of developed countries circular (Giampietro et al., 2019; Haas et al., 2015). Moreover, recycling rates differ (Giampietro et al., 2019), but the level of recirculation of consumable and durable products or their components is generally low—the average is well below 50% (Cullen, 2017). When considering the overall recycling rate, Haas et al. (2015) set a value of 13% over the whole input of 6.7 GT/year when including the recycling of construction material. Further, the large-scale recycling of materials may slow down the economic process, i.e. flows that were readily available for consumption need to be produced first and create a new energy demand (Giampietro et al., 2019).

Moreover, technological innovation may extend product durability and reduce the requirement of primary energy and agricultural resources. Increased efficiency, however, may lead to rebound effects such as the Jevons paradox. Therefore, technological innovations are not enough to transition to more circular economies. The CE in EU countries makes it possible to boost competitiveness and growth, stimulating local and regional development, creating new opportunities and jobs and avoiding irreversible environmental damage (EC, 2015). However, as noted earlier, empirical research assessing countries' transition to CE is scant (Table 2 presents a summary).

Table 2 Summary of related research

Authors	*Methods*	*Data focus*
Mavi and Mavi (2019)	Malmquist productivity index	OECD countries, 2012–2015
Giannakitsidou et al. (2020)	Data envelopment analysis	26 European Union countries, 2014 and 2017
Škrinjarić (2020)	Grey relational analysis	Selected European countries, 2010–2016
Marino and Pariso (2020)	Comparative statistical ratios analysis	28 EU Member States, 2006–2016
Škrinjarić (2020)	Data envelopment analysis	37 European countries, 2004–2016
Momete (2020)	Composite index	24 EU Member States, one year

Mavi and Mavi (2019) explore environmental issues arising from energy use and circularity. Hence, the authors analyse the energy and environmental efficiency of OECD countries using the Malmquist productivity index. The proposed model enables decision-makers to assess all the OECD countries on the same basis to reveal their strength and weaknesses. The results demonstrate that Switzerland had the highest efficiency during 2012–2014, while Ireland took first place in 2015.

Giannakitsidou et al. (2020) measure the environmental and CE performance of 26 EU countries. The study shows significant disparities among European countries concerning their performance. Interestingly, the borders between Western and Eastern Europe have fallen, but not those between the north and the south: early EU members, such as Spain and France, perform significantly worse—both from an environmental and CE perspective—than newer members like Slovenia and Poland.

Škrinjarić (2020) evaluates the CE achievements of select European countries and finds regional discrepancies among them. Namely, the best performing CE countries are Germany, the Netherlands, Denmark, France and Italy, with the worst performance appearing in Romania, Greece, Cyprus, Slovakia and Bulgaria. The best-performing countries have greater GDP per capita and better infrastructure, education and research and development (R&D). Marino and Pariso (2020) also find that the country's leading in CE development have a higher GDP in PPS and GDP/CEI ratio average values. The results confirm a correlation between these economic elements with the transition of the countries towards CE. Furthermore, in a further study, Škrinjarić (2020) indicates that the most inefficient countries have shown an increase in their sustainable development efficiency score from 2004–2016.

Momete (2020) assesses the readiness of EU economies to migrate from a linear economy to a circular one through a methodology that incorporates economic, social and environmental factors. Over 40% of EU Member States are ready to embark on a circular future. This percentage, which comprises both Western and Eastern European countries, reveals that circular modelling has great potential, especially in Western Europe.

Apart from empirical studies, it is also worth mentioning Moraga et al. (2019), who provide a conceptual overview of CE measurement indicators across different perspectives. To illustrate the framework with macro-scale indicators, the authors select the indicators recently proposed by the European Commission (2018), which we also applied in our study.

In sum, the literature review shows some empirical attempts to assess various aspects of countries CE performance. However, their primary focus is geographic and unrelated to country size and openness.

2.3 Circular economy: small open economies

Although there have been several studies on various aspects of CE, researchers (George et al., 2015; Hoogmartens et al., 2018) highlight the lack of CE assessment at different levels (especially at the country, region and industry levels). Most of the research is noticeably focused on large economies (such as the US, China, Japan, Germany and the UK), and it is argued that a large open economy can influence its domestic interest rates and substantially impacts world markets and the global interest rate. However, an SOE is assumed to be too small to influence the level of world output or the global interest rate (Carlin and Soskice, 2003). What constitutes an SOE and its characteristics varies. According to Chen et al. (2018), advanced SOEs have the following features:

1. their business cycle volatility is usually comparable in size to that seen in large wealthy economies
2. their consumption is less volatile than output
3. their interest rates are procyclical (an increase in economic activity is usually associated with an increase in interest rates today and in the near future).

It can be argued that in order for small economies to thrive, they need to focus on open trade through partnerships due to the ever-scarce resources and global environmental boundaries and challenges.

Moreover, since environmental boundaries and challenges are global, solving environmental threats requires close cooperation among industries and companies. This is extremely important to SOEs, which usually adjust to the policies carried out by large countries. EU countries have a significant influence on the world economy, but most EU countries are classified individually as SOEs. Thus, SOEs play a vital global role, but there is a lack of comprehensive analysis of CE implementation in SOEs. Recent research into CE in SOEs is focused on individual case studies of countries (such as Belgium, the Netherlands, Finland, Sweden and Denmark) and analyses resource productivity (Cainelli et al., 2020), best practices (Paquin et al., 2015; Su et al., 2013), drivers and barriers (Fischer and Pascucci, 2017; Ranta et al., 2018; Seth et al., 2018; Whalen et al., 2018) and opportunities and benefits (Geerken et al., 2019; Kumar et al., 2019). However, the main challenge for SOEs is competitiveness, which needs to be maintained when moving from a linear to a circular system due to dwindling resources. This focus is elaborated in the current research.

3 Research methodology

This section presents the methodology for analysing CE implementation strategies in SOEs based on a principal component analysis (PCA). The units of research are 13 advanced SOEs in the EU. The following sampling filters were used for the identification of advanced SOEs (Table 3):

- Small population. Traditionally, population size has been used as the metric to identify a small economy. This paper defines a small population as up to 20 million, according to OECD (2018) population statistics.
- Advanced. The International Monetary Fund (IMF, 2018) compiles an advanced economy list based on per capita income, export diversification and degree of integration into the global financial system.
- Trade openness—exports plus imports as a per cent of GDP. This paper filters trade openness by more than 100% (The Global Economy, 2018).

Two countries, namely Estonia and Luxembourg, were eliminated from the research as official data highly exceeded the group average. In Estonia, the indicator, namely the generalization of waste, excluding major mineral waste per GDP unit, exceeded the group average by 10 times (group average 70.20 kilograms per thousand-euro, average indicator of Estonia 704.35 kilograms per thousand euro). In the case of Luxembourg, indicator, namely trade in recyclable raw materials (export extra-EU28), lagged behind the group average 33,397 times (group average 868331 tonne, average indicator of Luxembourg 26 tonne). Therefore, these two countries should be analysed separately.

Table 3 Research sample of advanced SOEs in the EU

No.	*Countries*	*Small population*	*Advanced*	*Trade openness (%)*
1	Ireland	4,830,392	+	206.20
2	Austria	8,822,267	+	105.50
3	Belgium	11,398,589	+	175.65
4	Czech Republic	10,610,055	+	150.76
5	Denmark	5,781,190	+	103.79
6	Cyprus	864,236	+	130.29
7	Latvia	1,934,379	+	118.37
8	Lithuania	2,808,901	+	161.95
9	Malta	475,701	+	267.78
10	Netherlands	17,181,084	+	155.21
11	Slovakia	5,443,120	+	192.35
12	Slovenia	2,066,880	+	160.94
13	Sweden*	10,120,242	+	90.92

Notes: *Additionally, Sweden was introduced into the analysis as a country that is carrying out numerous CE-related initiatives. For example, a recent regulation in Sweden cuts the VAT charged on repair work and provides tax rebates for the labour costs of repairs.

Source: EC (2019)

Despite the unclear concept of CE, it has turned into defined action plans supported by specific indicators (Moraga et al., 2019), for example, the EU monitoring framework on CE progress (EC, 2018). Based on the Eurostat data availability for each country (Appendix A), the analysed period is 2010–2017. All 17 country-level indicators from the EU monitoring framework have been used. Three indicators related to competitiveness and innovation, namely persons employed in the circular economy sector, gross value added and gross investment in tangible goods in CE sectors, have been distinguished by the lack of data for six out of 13 analysed countries.

When a country was lacking several years of data, a prediction was conducted as follows. If only intermediate values were missing in the data, the missing value was filled in with the mean of the adjacent values. If the missing value was at the end or beginning of a time series, then linear regression models with a coefficient of determination satisfying the regression conditions were used to predict this value.

The Czech Republic, Estonia, Ireland, Luxembourg, Malta and Slovenia did not provide any data for the indicators persons employed in CE sectors, gross value added and gross investment in tangible goods in CE sectors. Linear regression models predicted these indicators to maintain a coefficient of determination that was as high as possible. The employment indicator was projected based on each country's employment level compared to the average share of persons employed in CE sectors among the analysed group of SOEs. The indicators gross value added and gross investment in tangible goods in CE sectors were projected based on an individual country's level of gross value added and investment in tangible goods compared to the average share of gross value added and investment in CE sectors of the analysed group of SOEs.

Related to the specific methodology applied, a principal components analysis (PCA) was used to identify the strategies of CE implementation among SOEs. The selected 17 indicators of the EU monitoring framework are highly correlated, and PCA has been used for data reduction to learn more deeply about the underlying structure of the set of indicators. Before applying the PCA procedure, a KaisereMeyereOlkin measure of sampling adequacy (KMO) and a Bartlett test of sphericity (p-value) were performed to test for partial correlation and dependence for excluding the potential non-independence of the original data, which can affect the result of a PCA. For applicable data, KMO should demonstrate a value > 0.6. Bartlett's test of sphericity should be significant ($p < 0.05$). The Euclidean distance between the PCA dimensions was used to perform k-means clustering among the countries. A square error function between clusters was used to determine the optimal number of clusters (3). The number is determined based on the principle of the elbow. Hierarchical clustering and dendrograms were also performed.

To indicate the degree of homogeneity or heterogeneity of dispersion for each variable among the clusters, we calculated coefficients of variations (CV=Standard Deviation (SD)/Mean) (Appendix C). The CVs were sorted by size: the larger, the more heterogeneous; the smaller, the more homogeneous in their respective distribution and dispersion among clusters. To build the profiles of CE implementation strategies, the average indicator of each cluster was compared to the average indicator of all analysed SOEs. A five-level scale was used for comparison: deviation from the average +/- 5 percent: insignificant (0); +/- 5–15 percent: high (+) or low (-); more than +/- 15 percent: very high (++) or very low (--).

4 Results

The following subsections summarise the change analysis of principal components for CE progress and implementation strategies. It should be noted that the empirical research covers the period 2010–2017. The year 2010 occurs two years after the implementation of the waste management directive (2008); the year 2017 represents two years after the EU announced CE as a growth strategy.

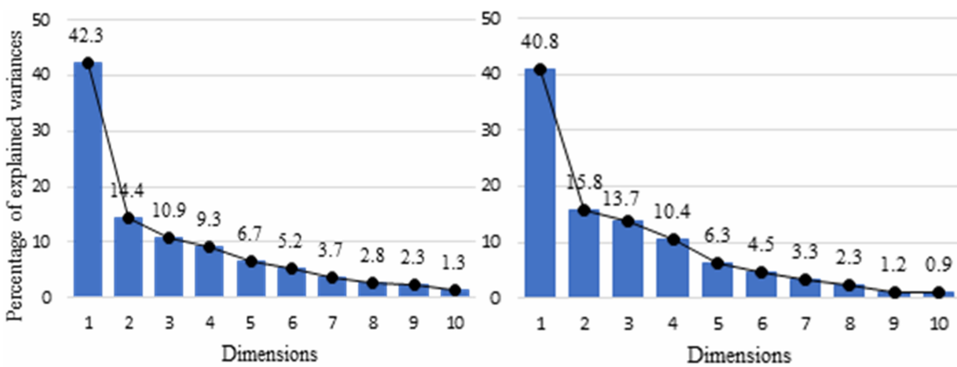
4.1 PCA results of circular economy indicators

The principal components identified and their changes from 2010 to 2017 show different directions in the areas of the EU monitoring framework for the circular economy, namely production and consumption, waste management, secondary raw materials and competitiveness and innovation.

In 2010, the PCA analysis shows that Dimensions 1 and 2 are the most important and can explain 56.7% (respectively, 42.3% and 14.4%) of CE implementation (Fig. 1a). In 2017, Dimensions 1 and 2 distributed very similarly, i.e., 56.6% (respectively, 40.8% and 15.8%) of CE implementation [Figure 1 (b)].

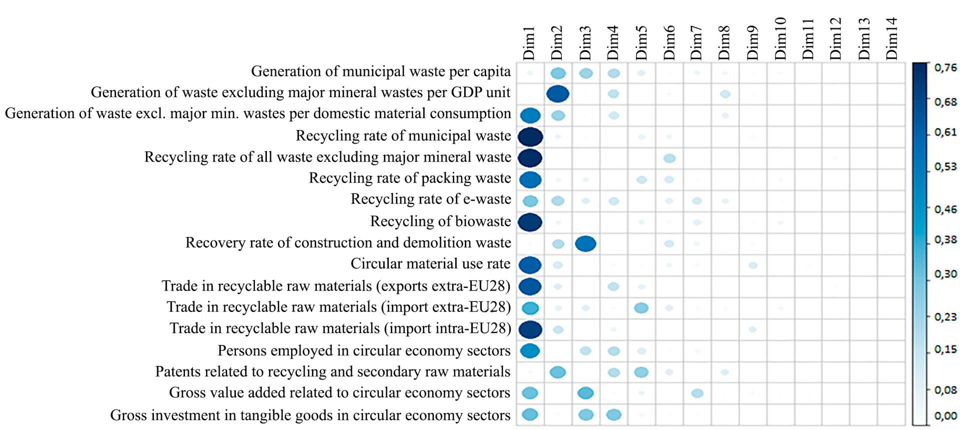
Figures 2 and 3 (as well as Appendix B) show the distribution of principal components (i.e., CE indicators) across dimensions in 2010 and 2017.

Figure 1 Decomposition of the total inertia on PCA components (%),(a) 2010 (b) 2017 (see online version for colours)



(a) (b)

Figure 2 CE implementation in advanced SOes (2010) (see online version for colours)

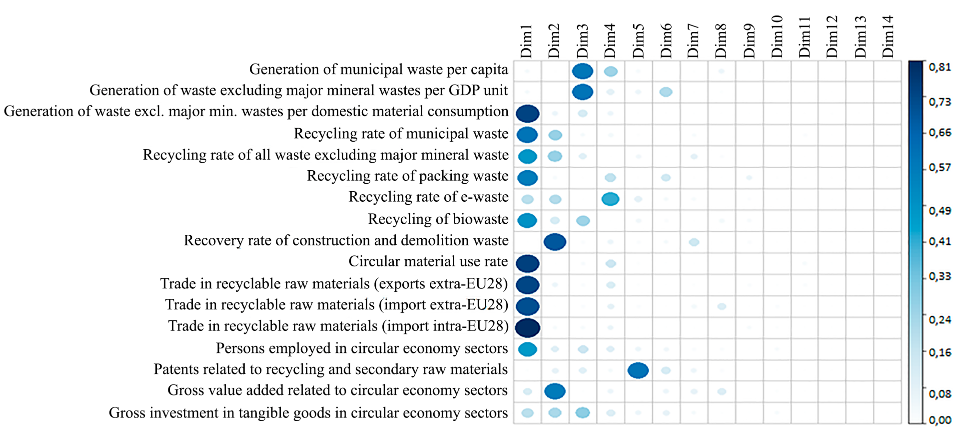


Based on the PCA analysis, the key areas from the EU monitoring framework covered are waste management and secondary raw materials that mainly explain countries' CE implementation in 2010 and 2017. However, the distribution and development of CE indicators differ over time.

Waste management indicates the recycling rates of municipal waste and all waste (excluding major mineral waste) and the percentage of specific waste streams that was recycled or recovered. As expected, different recycling ratios, except for the *recycling rate of e-waste* (7) and *recovery rate of construction* and demolition waste (9), have solid or average correlations and therefore are significant in measuring CE progress. The analysed countries improved their waste collection and recycling systems, as waste management has been a long-term focus of EU countries. Therefore, the positive influence has been caused by regulatory, institutional factors, e.g., the Waste Framework Directive (2008).

Interestingly, ratios related to the usage of secondary raw materials (circular material use rate (10), exports of recyclable raw materials to non-EU countries (11), intra-EU trade in recyclable raw material (13)) also were significant in 2010. However, the shift to implement economic policies through secondary raw materials, followed by waste management, grew after the adoption of the EU Circular Economy plan. In 2017, all indicators for secondary raw materials, namely, circular material use rate (10), exports of recyclable raw materials to non-EU countries (11), imports of recyclable raw materials from non-EU countries (12) and intra-EU trade in recyclable raw material (13) have strong correlations. The trade of recyclable raw materials, especially exports to non-EU countries, became more intensive during the analysed period, and this shows a positive iteration with competitiveness and countries' increasing global participation in international trade.

Figure 3 CE implementation in advanced SOEs (2017) (see online version for colours)



At a basic level, production and consumption measure how much waste is being generated and collected per country. Simply speaking, it may reflect the reduction principle. From the EU monitoring framework, waste generation indicators (such as generation of municipal waste per capita (1) and generation of waste excluding major mineral wastes per GDP unit (2)) were insignificant in both periods. Only one ratio, generation of waste per domestic material consumption (3), grew in relevance from 2010 to 2017. If a country strongly follows a linear economy approach and implements too few circularity principles (e.g., low recycling rates), it will generate excess waste (if it is competitive and has high productivity).

Another interesting observation obtained from the PCA analysis refers to the monitoring area competitiveness and innovation. Currently, these indicators fail to explain a higher level of CE implementation. As concerns private investment, jobs and gross value added related to CE sectors, only persons employed (16) had moderate correlations as well as value added at factor cost (18) in 2017.

The comparison PCA analysis clearly indicates the shift from waste management (recycling ratios) to close the loop through the usage of secondary raw materials in manufacturing. Further, waste generation and collecting schemes improved. However, we cannot find evidence for the expansion of CE related sectors through persons employed, value added or gross investments.

The following section will introduce what strategies for CE implementation could be found among countries and discuss how they changed from 2010 to 2017.

4.2 Clustering results of circular economy implementation strategies

A PCA was carried out to determine a group of countries with a similar profile of CE implementation strategies. The optimal number of clusters was determined based on the inertia gain obtained. During the implementation of this approach, the countries were assigned to three clusters; no outliers were determined.

Figures 4(a) and 4(c) illustrate the scattering of countries as clusters adequately based on Dimension 1 and Dimension 2, while Figures 4(b) and 4(d) reveal the hierarchical grouping of countries into clusters in 2010 and 2017.

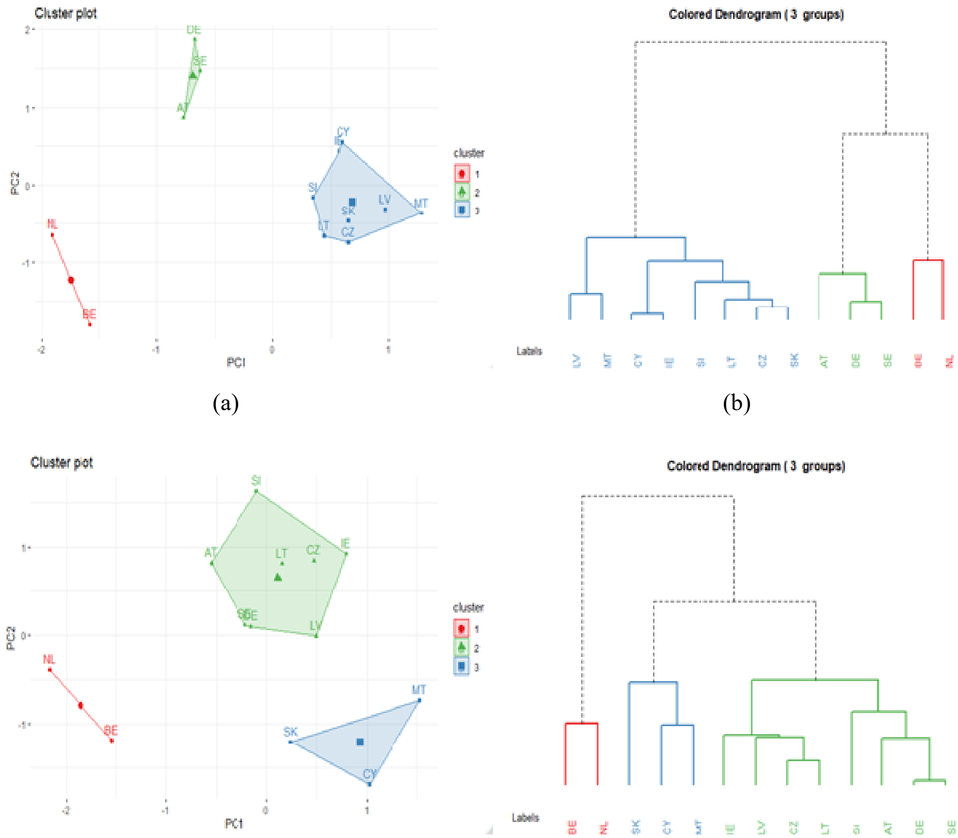
As illustrated in Figure 4, all countries were classified into three separate clusters:

- Cluster 1 consisted of the Netherlands and Belgium
- Cluster 2 in 2010 consisted of Denmark, Sweden and Austria, which were joined in 2017 by four more countries (initially Cluster 3): Slovenia, Lithuania, the Czech Republic and Ireland.
- Cluster 3 consisted of Latvia, Malta, Cyprus, Ireland, Slovakia, Lithuania, Slovenia and the Czech Republic in 2010, decreasing by four countries in 2017.

In 2010, one cluster, and in 2017, two clusters are larger than the rest. Two countries were assigned to Cluster 1 in 2010 and 2017; eight countries to Cluster 2 in 2010 and four in 2017; three countries to Cluster 3 in 2010 and seven countries in 2017. Four countries were transferred from Cluster 3 to Cluster 2 in 2017. The dendrograms [Figures 4(b)–4(d)] reveal how the countries were merged into clusters.

In the following, a detailed description of each cluster (Table 4 and Appendix C) is presented to build profiles of countries' CE implementation strategies. Based on clustering results, we have identified three profiles of countries' CE implementation strategies, namely, integrated to value chain (matching Cluster 1), focused on compliance (matching Cluster 2) and fragmented (matching Cluster 3).

Figure 4 Hierarchical clustering of countries, (a) clusters in the plane in 2010 (b) cluster dendrogram in 2010 (c) clusters in the plane in 2017 (d) cluster dendrogram in 2017 (see online version for colours)



(a) (b)

(c) (d)

Countries that develop an integrated to value chain strategy include CE issues in their economic growth and competitiveness strategies. This profile may be characterised as having well-developed waste management systems with no significant fluctuations in persons employed and CE investments. Trade in recyclable raw materials occurs at a high level. Although waste generation indicators are quite high, a well-developed waste management system and trade in recyclable raw materials balance the performance of the total economy. In this case, the integrated strategy expresses a higher level of collaboration among main CE actors and indicates a more mature CE development stage. However, the area of competitiveness and innovation needs additional attention.

Countries that develop a focused-on compliance strategic profile also systematically include CE issues in their economic growth strategies, but these countries mainly seek to comply with the legal and mandatory requirements of EU directives. The following features may characterise the compliance profile: greater focus on the development of a waste management system, investment and innovation related to CE and less collaboration among main CE actors.

Table 4 Characterisation of clusters in 2010 and 2017

Indicators		*Cluster 1*	*Cluster 2*	*Cluster 3*	*Cluster 1*	*Cluster 2*	*Cluster 3*
		2010			*2017*		
Waste generation							
1	Generation of municipal waste per capita	0	+	-	+	0	0
2	Generation of waste, excluding major mineral waste per GDP unit	+	--	+	++	--	--
3	Generation of waste, excluding major mineral waste per domestic material consumption	++	-	-	++	+	--
Waste management							
4	Recycling rate of municipal waste	++	++	--	++	+	--
5	Recycling rate of all waste, excluding major mineral waste	++	+	-	++	0	--
6	Recycling rate of packaging waste	++	+	-	++	0	--
7	Recycling rate of e-waste	+	++	--	0	+	--
8	Recycling of biowaste	++	++	--	++	+	--
9	Recovery rate of construction and demolition waste	-	++	-	-	+	--
Secondary raw materials							
10	Circular material use rate	++	0	---	++	--	--
11	Trade in recyclable raw materials (exports extra-EU28)	++	--	--	++	--	--
12	Trade in recyclable raw materials (imports extra-EU28)	++	++	--	++	--	--
13	Trade in recyclable raw materials (imports intra-EU28)	++	-	--	++	--	--
Competitiveness and innovation							
14	Persons employed in circular economy sectors	--	--	++	--	+	+
15	Patents related to recycling and secondary raw materials	++	--	0	++	0	--
16	Gross value added related to circular economy sectors	-	-	0	--	+	-
17	Gross investment in tangible goods in circular economy sectors	--	--	++	--	+	0

Notes: Deviation from the average +/– 5%: insignificant (0); +/– 5–15%: high (+) or low (–); more than +/– 15%: very high (++) or very low (--).

The fragmented profile chiefly pays attention to CE infrastructure creation and employment. This is an early or introductory CE development stage. Simultaneously, these countries generate a higher level of municipal waste and develop infrastructure by employing more persons and innovations. The eco-system of trade in recyclable raw materials and waste management is still under development. In this case, a collaboration among main CE actors is fragmented.

5 Discussion

We found that in advanced SOEs, CE is implemented chiefly through waste management. This is in line with key trends throughout the EU. Between 2004 and 2016, the amount of waste generated, excluding major mineral waste, decreased by 6.5% in the EU. Between 2004 and 2014, the EU recycling rate rose slightly from 53% to 55%. It is important to note that there should be a similar trend in the future: there is a common EU target to recycle 65% of municipal waste and 75% of packaging waste by 2030; material-specific targets exist for different packaging materials, and there is a binding landfill reduction target of 10% by 2030.

The implementation of CE is spread across micro, meso and macro levels: the actors are the same, but their motives differ. CE implementation is being encouraged mostly by countries' policies (e.g., waste management directives, CE action plans) and is increasingly sensitive to legislation. When it comes to competitiveness, each country is creating and implementing a distinct strategy, while CE goals are part of the overall EU agenda. Despite controversial discussions, our findings support 'boosting countries' competitiveness through CE' (EC, 2019), which in turn may guide policymaking.

We elaborated three profiles of CE implementation strategies in relation to CE development stages: integrated to value chains matches the mature CE development stage, focused on compliance is related to growing CE importance to the economic development stage and fragmented matches the early or introductory CE development stage. An integrated profile might serve as a CE implementation model for SOEs, fulfilling a higher level of collaboration among leading CE actors at institutional and organisational levels. Meanwhile, the focused and fragmented profiles clearly show the lack of integrating CE into value chains. We emphasise the deep analysis of best practices among Cluster 1 and Cluster 2 countries, especially those that transitioned from Cluster 3 to Cluster 2.

Only two countries from the analysed SOEs, namely the Netherlands and Belgium, integrated CE within the entire value chain, i.e., waste collection, higher levels of recycling and recovery ratios and the usage of secondary raw materials. Belgium has been revealed as the best performer, both from an environmental and a cyclical economy perspective, as noted in Giannakitsidou et al. (2020). Surprisingly, we found a low integration of persons employed in CE sectors by cluster, which is described as integrated value chains. Although a vast amount of research emphasises a significant increase in jobs, our empirical research overall shows a gradual decrease. Worldwide employment would grow by 0.1% by 2030 compared to a business-as-usual scenario, particularly in the service and waste management sectors, by roughly 50 million and 45 million jobs, respectively (ILO, 2018a). Moreover, Cambridge Econometrics (2018) has forecast that CE could add 0.5% to Europe's GDP and a net increase of 700,000 jobs—mainly located in Central and Eastern European Member States—by shifting labour from current resource extraction activities to more labour-intensive recycling plants and repair services.

In our opinion, the obtained results might be explained by methodological shortages. The data about persons employed in CE sectors included in the Eurostat classification do not cover all sectors related to the CE. Principally, CE jobs are core activities that preserve and extend what is already made (reuse and recycle) and thus are indirectly circular (data analyst and design for future). More importantly, Eurostat data covers mainly core jobs, i.e., the recycling, repair and reuse, and rental and leasing sectors. Furthermore, only 42% of total Dutch CE jobs align well with the Eurostat classification, while a 2017 report by Circle Economy and Ehero estimates that 8% of the Dutch workforce is currently employed in CE jobs. In the past 15 years, activities that involve 'repair and maintenance' have remained stable, with the 'incorporation of digital technologies' appearing as an up-and-coming job provider. We anticipate that the impact of digital technologies will be more substantial for indirect jobs in comparison to core jobs in CE because of their maturity.

Another important observation that deserves deeper discussion is the challenge of implementing the EU monitoring framework for CE. In line with the critical analysis of CE indicators discussed by Mayer et al. (2018), it is crucial to increase statistical reporting. Waste-related indicators (both waste generation and recycling) comprise 47.4%. Given the context of competitiveness, less waste generation may be related more to productivity than CE. Therefore, we recommend revising the framework by adding more economic indicators, which are integral to industrial symbiosis. Countries' monitoring of CE implementation is crucial for long-term EU policy objectives. Therefore, data gathering and monitoring systems in each country are essential for updating CE implementation and timely decision-making.

From a theoretical perspective, our research has implications for institutional theory by matching typologies of strategies towards CE with CE development stages. We also contribute to the debate on CE development in SOEs that lack attention in the scientific literature compared to large economies. We believe that a comprehensive understanding of CE monitoring indicators and the characteristics of CE implementation strategies will help policymakers improve and redesign directives for economic growth by prioritising CE. Promoting CE may have a slower start due to substantial costs, upfront technological investments, social innovations and acceleration driven by the cumulative effect on competitiveness.

6 Limitations and directions for further research

We also concede that data-related limitations hampered our research. The selection of indicators was based on the availability of data and prediction accuracy. Two indicators from the area of production and consumption (namely, food waste and green procurement) are currently under development; other indicators are biannual, and some indicators are data-limited (further details in Appendix A).

There are several future research opportunities available because this is still a novel research area in the economic development literature. The need for conceptual research into CE measurements at different scales leads to systemic integration of CE indicators and may improve the EU monitoring framework for the circular economy. An in-depth change analysis of PCA, which combines quantitative data and the content analysis of strategic documents, should be undertaken. A further option includes a larger sample of countries by adding and comparing CE implementation strategies among SOEs, large economies and non-EU SOEs. We also recommend developing and improving scenario-based models to elaborate upon CE implementation patterns in future research.

7 Conclusions

The PCA analysis results clearly indicate the shift from waste management (recycling ratios) to a closure of the loop through the usage of secondary raw materials and the trade in recyclable materials. In addition, waste generation and collecting schemes improved. Nevertheless, we did find evidence for the expansion of CE related sectors through persons employed, value added or gross investments. Thus far, the results allow us to conclude that reasonable institutional policies and actions impact CE. The results support the EU political agenda and the current scientific consensus, which states that CE emerges gradually and is visible only over time.

In addition, we built profiles of countries' CE implementation strategies based on the EU monitoring framework for CE. The countries that prioritised waste management issues and the development of secondary raw materials market match the integrated to value chains profile. Focus on a compliance strategy confirms the importance of institutionalisation, as countries seek to achieve legal guidelines set by EU directives. Our results also support the conclusion that countries could shift from fragmented and focused profiles by adopting CE development tools, such as collaboration among main CE actors. The findings are important for fostering a circular environmental approach across EU countries.

Acknowledgements

This work was supported by the Research Council of Lithuania (LMTLT), contract no. S-MIP-19-38 under the project title "Circular economy modelling and empowerment perspective in small open economy" (CEMESOE).

References

Alvarez-Risco, A., Del-Aguila-Arcentales, S., Rosen, M.A., García-Ibarra, V., Maycotte-Felkel, S., Martínez-Toro, G.M. (2021). 'Expectations and interests of university students in COVID-19 times about sustainable development goals: evidence from Colombia, Ecuador, Mexico, and Peru', *Sustainability*, Vol 13, No. 6, pp.3306, https://DOI.org/10.3390/su13063306.

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., and Calabretta, G. (2019) 'Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives', *Journal of Cleaner Production*, Vol. 216, https://DOI.org/10.1016/j.jclepro.2019.01.091.

Cainelli, G., D'Amato, A., and Mazzanti, M. (2020) 'Resource efficient eco-innovations for a circular economy: evidence from EU firms', *Research Policy*, Vol. 49 No. 1, https://DOI.org/10.1016/j.respol.2019.103827.

Cambridge Econometrics, Trinomics, and ICF. (2018) *Impacts of Circular Economy Policies on the Labour Market* [online] https://circulareconomy.europa.eu/platform/sites/default/files/ec_2018__impacts_of_circular_economy_policies_on _the_labour_market.pdf (accessed 14 January 2020).

Carlin, W. and Soskice, D. (2003) *The Open Economy – Draft Chapter* [online] http://www.ucl.ac.uk/~uctpa36/ch4march403.pdf (accessed 28 January 2020).

Chen, K.J., Chu, A., and Lai, C.C. (2018) 'Home production and small open economy business cycles', *Journal of Economic Dynamics and Control*, Elsevier, Vol. 95, No. C, pp.110–135, https://DOI.org/10.1016/j.jedc.2018.08.001.

Circle Economy. (2018) *The Circularity Gap Report* [online] https://www.circularity-gap.world/ (accessed 16 January 2020).

Circle Economy and Ehero. (2017) *Circular Jobs: Understanding Employment and Circular Economy in the Netherlands* [online] https://www.circle-economy.com/wp-content/uploads/2017/03/goldschmeding-jobs-report-20170322-lite.pdf (Accessed 14 January 2020).

Cullen, J.M. (2017) 'Circular economy: theoretical benchmark of perpetual motion machine?', *Journal of Industrial Ecology*, Vol. 21 No. 3, pp.483–486, https://DOI.org/10.1111/jiec.12599.

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J. Leskinen, P., Matthies, B.D., and Toppinen, A. (2017) 'Green, circular, bio economy: a comparative analysis of sustainability avenues', *Journal of Cleaner Production*, Vol. 168, pp.716–734, https://DOI.org/10.1016/j.jclepro.2017.09.053.

Davies, G.G. and Hall, J.A. (2006) Circular Economy Legislation? The International Experience. siteresources.worldbank.org/.../CircularEconomy_Legal_IntExperience_ExecSummar (Accessed 3 December 2019).

Elia, V., Gnoni, M.G., and Tornese, F. (2017) 'Measuring circular economy strategies through index methods: a critical analysis', *Journal of Cleaner Production*, Vol. 142, pp.2741–2751, https://DOI.org/10.1016/j.jclepro.2016.10.196.

Ellen MacArthur Foundation and the McKinsey Center for Business and Environment. (2015) Growth within: A circular economy vision for a competitive Europe. [online] https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf (Accessed 3 December 2019).

European Commission. (2015) An EU Action Plan for the Circular Economy. [online] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0614 (Accessed 29 January 2020).

European Commission. (2018) Monitoring framework on the circular economy. [online] https://ec.europa.eu/eurostat/web/circular-economy/indicators (Accessed 12 January 2020).

European Commission. (2018a) Circular Economy. Closing the loop – Clear targets and tools for better waste management. [online] https://ec.europa.eu/commission/sites/beta-political/files/circular-economy-factsheet-waste-management_en.pdf (Accessed 2 February 2020).

European Commission. (2019) Reflection paper 'Towards a Sustainable Europe by 2030. [online] https://ec.europa.eu/commission/sites/betapolitical/files/rp_sustainable_europe_30-01_en_web.pdf (Accessed 12 January 2020).

European Commission. (2020) Circular Economy Action Plan. For a cleaner and more competitive Europe. [online] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf (Accessed 20 April 2021).

Eurostat database. (2020) [online] https://ec.europa.eu/eurostat/data/database (Accessed 5 January 2020).

Fischer, A. and Pascucci, S. (2017) 'Institutional incentives in circular economy transition: the case of material use in the Dutch textile industry', *Journal of Cleaner Production*, Vol. 155, pp.17–32, https://DOI.org/10.1016/j.jclepro.2016.12.038.

Geerken, T., Schmidt, J., Boonen, K., Christis, M., and Merciai, S. (2019) 'Assessment of the potential of a circular economy in open economies – Case of Belgium', *Journal of Cleaner Production*, Vol. 227, pp.683–699, https://DOI.org/10.1016/j.jclepro.2019.04.120.

Geng, Y., Fu, J., Sarkis, J. and Hue, B. (2012) 'Towards a national circular economy indicator system in China: an evaluation and critical analysis', *Journal of Cleaner Production*, Vol. 23 No. 1, pp.216–224, https://DOI.org/10.1016/j.jclepro.2011.07.005.

George, D.A.R., Chi-ang Lin, B., and Chen, Y. (2015) 'A circular economy model of economic growth', *Environmental Modelling and Software*, Vol. 73, pp.60–63, https://DOI.org/10.1016/j.envsoft.2015.06.014.

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016) 'A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems', *Journal of Cleaner Production*, Vol. 114, pp.11–32, https://DOI.org/10.1016/j.jclepro.2015.09.007.

Giampietro, M., Kovacic, Z., Strand, R., and Voelker, T. (2019) *Report on Narratives behind Circular Economy Concept* [online] https://magicnexus.eu/sites/default/files/files_documents_repository/magic_deliverable-5.7_revision_24.06.2019.pdf (Accessed 17 January 2020).

Giannakitsidou, O., Giannikos, I., and Chondrou, A. (2020) 'Ranking European countries on the basis of their environmental and circular economy performance: a DEA application in MSW', *Waste Management*, Vol. 109, pp.181–191, https://DOI.org/10.1016/j.wasman.2020.04.055.

Haas, W., Krausmann, F., Wiedenhofer, D., and Heinz, M. (2015) 'How circular is the global economy? an assessment of material flows, waste production, and recycling in the European Union and the world in 2005', *Journal of Industrial Ecology*, Vol. 19 No. 5, pp.765–777, https://DOI.org/10.1111/jiec.12244.

Homrich, A.S., Galvao, G., Abadia, L.G., and Carvalho, M.M. (2018) 'The circular economy umbrella: trends and gaps on integrating pathways', *Journal of Cleaner Production*, Vol. 175, pp.525–543, https://DOI.org/10.1016/j.jclepro.2017.11.064.

Hoogmartens, R., Eyckmans, J. and Passel, S.V. (2018) 'A hotelling model for the circular economy including recycling, substitution and waste accumulation', *Resources, Conservation and Recycling*, Vol. 128 No. 1, pp.98–109, https://DOI.org/10.1016/j.resconrec.2017.09.015.

International Labour Organization. (2018) *Decent Work* [online] https://www.ilo.org/global/topics/decentwork/ lang--en/index.html (accessed 12 December 2019).

International Monetary Fund List. (2018) 'World economic outlook, April 2018: cyclical upswing', *Structural Change*, p.220 [online] https://www.imf.org/en/Publications/WEO/Issues/2018/03/20/world-economic-outlook-april-2018 (accessed 16 December 2019).

Kirchherr, J., Reike, D. and Hekkert, M. (2017) 'Conceptualizing the circular economy: an analysis of 114 definitions', *Resources, Conservation and Recycling*, Vol. 127, pp.221–232, https://DOI.org/10.1016/j.resconrec.2017.09.005.

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., and Hekkert, M. (2018) 'Barriers to circular economy: evidence from the European Union (EU)', *Ecological Economics*, Vol. 150, pp.264–272, https://DOI.org/10.1016/j.ecolecon.2018.04.028.

Korhonen, J., Nuur, C., Feldmann, A., and Birkie, S.E. (2018) 'Circular economy as an essentially contested concept', *Journal of Cleaner Production*, Vol. 175, pp.544–552, https://DOI.org/10.1016/j.jclepro.2017.12.111.

Kumar, V., Sezersan, I., Garza-Reyes, J.A., Gonzalez, E.D.R.S., and AL-Shboul, M.A. (2019) 'Circular economy in the manufacturing sector: benefits, opportunities and barriers', *Management Decision*, Vol. 57 No. 4, pp.1067–1086, https://DOI.org/10.1108/MD-09-2018-1070.

Lieder, M. and Rashid, A. (2016) 'Towards circular economy implementation: a comprehensive review in the context of manufacturing industry', *Journal of Cleaner Production*, Vol. 115, pp.36–51, https://DOI.org/10.1016/j.jclepro.2015.12.042.

Marino, A. and Pariso, P. (2020) 'Comparing European countries' performances in the transition towards the circular economy', *Science of The Total Environment*, Vol. 729, https://DOI.org/10.1016/j.scitotenv.2020.138142.

Mavi, N.K. and Mavi, R.K. (2019) 'Energy and environmental efficiency of OECD countries in the context of the circular economy: Common weight analysis for Malmquist productivity index', *Journal of Environmental Management*, Vol. 247, pp.651–661, https://DOI.org/10.1016/j.jenvman.2019.06.069.

Mayer, A., Haas, V., Wiedenhofer, D., Krausmann, F., Nuss, P., and Blengini, G.A. (2018) 'Measuring progress towards a circular economy - a monitoring framework for economy-wide material loop closing in the EU28', *Journal of Industrial Ecology*, Vol. 23 No. 1, pp.62–76.

Momete, D.C. (2020) 'A unified framework for assessing the readiness of European Union economies to migrate to a circular modelling', *Science of The Total Environment*, Vol. 718, pp.137–375, https://DOI.org/10.1016/j.scitotenv.2020.137375.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Ackerd, K., de Meester, S., and Dewulfa, J. (2019) 'Circular economy indicators: what do they measure?', *Resources, Conservation and Recycling*, Vol. 146, pp.452–461, https://DOI.org/10.1016/j.resconrec.2019.03.045.

Murray, A., Skene, K. and Haynes, K. (2017) 'The circular economy: an interdisciplinary exploration of the concept and application in a global context', *Journal of Business Ethics*, Vol. 140, No. 3, pp.369–380.

OECD. (2017) *The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches* [online] http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPRPW/WPIEEP(2017)1/FINAL&docLanguage=En (accessed 12 January 2020).

OECD. (2018) *Population* [online] https://data.oecd.org/pop/population.html (accessed 26 January 2020).

Paquin, R.L., Busch, T., and Tilleman, S.G. (2015) 'Creating economic and environmental value through industrial symbiosis', *Long Range Planning*, Vol. 48, No. 2, pp.95–107.

Parchomenko, A., Nelen, D., Gillabel, J. and Rechberger, H. (2019) 'Measuring the circular economy - a multiple correspondence analysis of 63 metrics', *Journal of Cleaner Production*, Vol. 210, pp.200–216, https://DOI.org/10.1016/j.jclepro.2018.10.357.

Ranta, V., Aarikka-Stenroos, L., Ritala, P., and Mäkinen, S.J. (2018) 'Exploring institutional drivers and barriers of the circular economy: a cross-regional comparison of China, the US, and Europe', *Resources, Conservation and Recycling*, Vol. 135, pp.70–82, https://DOI.org/10.1016/j.resconrec.2017.08.017.

Santagata, R., Zucaro, A., Viglia, S., Ripa, M., Tian, X., and Ulgiati, S. (2020) 'Assessing the sustainability of urban eco-systems through energy-based circular economy indicators', *Ecological Indicators*, Vol. 109, 105859, https://DOI.org/10.1016/j.ecolind.2019.105859.

Seth, D., Rehman, M.A.A., and Shrivastava, R.L. (2018) 'Green manufacturing drivers and their relationships for small and medium (SME) and large industries', *Journal of Cleaner Production*, Vol. 198, pp.1381–1405, https://DOI.org/10.1016/j.jclepro.2018.07.106.

Su, B., Heshmatia, A., Geng, Y., and Yub, X. (2013) 'A review of the circular economy in China: moving from rhetoric to implementation', *Journal of Cleaner Production*, Vol. 42, pp.215–227, https://DOI.org/10.1016/j.jclepro.2012.11.020.

Škrinjarić, T. (2020) 'Empirical assessment of the circular economy of selected European countries', *Journal of Cleaner Production*, Vol. 255. pp. 1-17, https://DOI.org/10.1016/j.jclepro.2020.120246.

Škrinjarić, T. (2020) 'Re-examining sustainable development in Europe: a data envelopment approach', *International Journal of Environment and Sustainable Development*, Vol. 19, No. 1, pp.72–108.

The Global Economy. (2018) *Trade Openness* [online] https://www.theglobaleconomy.com/rankings/trade _openness/European-union/ (accessed 14 January 2020).

Whalen, K.A., Milios, L., and Nussholz, J. (2018) 'Bridging the gap: barriers and potential for scaling reuse practices in the Swedish ICT sector', *Resources, Conservation and Recycling*, Vol. 135, pp.123–131.

Appendices

Appendix A

Table A1 Indicators of EU monitoring framework on CE

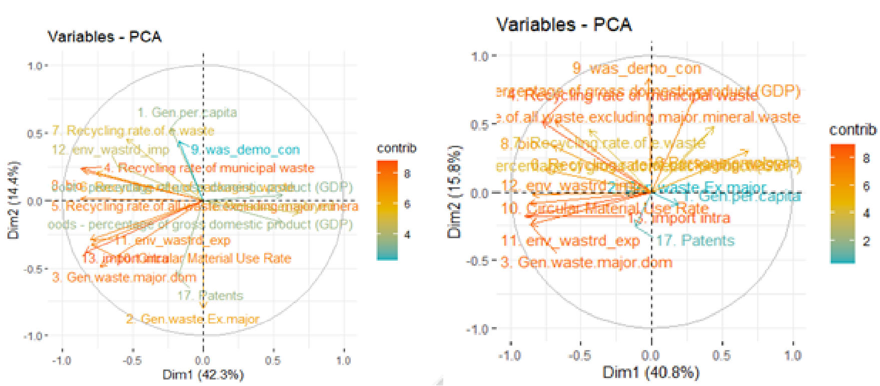
Sub-index (directions or areas)	*Indicators*		
Production and consumption	Waste generation		
	1	Generation of municipal waste per capita (available; no data for some years: Denmark, Ireland)	
	2	Generation of waste, excluding major mineral waste per GDP unit (available each second year)	
	3	Generation of waste, excluding major mineral waste per domestic material consumption (available each second year)	
		Green public procurement (as a financing indicator) – under development	
		Food waste – under development	
		Self-sufficiency of raw materials for production in the EU – only EU level	
Waste management	Overall recycling rates		Six indicators were selected for calculation
	4	Recycling rate of municipal waste (available; no data for some years: Denmark, Ireland)	
	5	Recycling rate of all waste, excluding major mineral waste (available each second year, no data for Latvia	
	Recycling rates of specific waste streams		
	6	Recycling rate of packaging waste by type of packaging (available)	
	7	Recycling rate of e-waste (available)	
	8	Recycling of biowaste (available; no data for some years: Denmark, Ireland)	
	9	Recovery rate of construction and demolition waste (available each second year; no data for some years: Denmark, Latvia, Slovakia)	
Secondary raw materials	Contribution of recycled materials to raw material demand – only EU level		Four indicators were selected for calculation
	10	Circular material uses rate (available) Trade of recyclable raw materials among EU Member States and abroad	
	11	Trade in recyclable raw materials (import extra-EU28) (available)	
	12	Trade in recyclable raw materials (exports extra-EU28) (available)	
	13	Trade in recyclable raw materials (imports intra-EU28) (available)	

Table A1 Indicators of EU monitoring framework on CE (continued)

Sub-index (directions or areas)		*Indicators*	
Competitiveness and innovation		Private investments, jobs, and gross value added related to circular economy sectors	Four indicators were selected for calculation
	14	Gross value added related to circular economy sectors (value added % of GDP) (no data: Czech Republic, Ireland, Luxembourg, Malta; some years: Belgium, Cyprus, Estonia, Finland)	
	15	Gross investment in tangible goods in circular economy sectors (% of GDP) (no data: Czech Republic, Ireland, Luxembourg, Malta; some years: Cyprus, Belgium, Estonia, Finland, Slovenia)	
	16	Persons employed in circular economy sectors (% of total employment) (no data: Czech Republic, Ireland, Luxembourg, Malta; some years: Belgium, Cyprus, Estonia, Finland, Slovenia)	
	17	Patents related to recycling and secondary raw materials (available, no data for 2016)	

Appendix B

Figure B1 The distribution of principal components



(a) 2010 (b) 2017

Appendix C

Coefficients and indicators of clusters

Table C1 Coefficient of variations among clusters in 2010 and 2017

Indicators	*2010*			*2017*		
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 1*	*Cluster 2*	*Cluster 3*
Generation of municipal waste per capita	0.16	0.30	0.30	0.16	0.25	0.27
Generation of waste, excluding major mineral waste per GDP unit	0.33	0.10	0.33	0.24	0.44	0.46
Generation of waste, excluding major mineral waste per domestic material consumption	0.03	0.06	0.33	0.01	0.21	0.29
Recycling rate of municipal waste	0.08	0.13	0.71	0.01	0.24	0.65
Recycling rate of all waste, excluding major mineral waste	0.04	0.08	0.24	0.08	0.24	0.26
Recycling rate of packaging waste	0.05	0.13	0.23	0.05	0.08	0.40
Recycling rate of e-waste	0.06	0.23	0.39	0.06	0.12	0.76
Recycling of biowaste	0.25	0.51	1.44	0.40	0.63	1.11
Recovery rate of construction and demolition waste	1.00	0.09	0.70	0.64	0.09	0.26
Circular material use rate	0.47	0.10	0.75	0.36	0.49	0.49
Trade in recyclable raw materials (exports extra-EU28)	0.32	0.65	0.74	0.26	0.84	0.42
Trade in recyclable raw materials (import extra-EU28)	0.72	1.08	1.37	0.64	1.23	1.12
Trade in recyclable raw materials (imports intra-EU28)	0.19	0.88	0.89	0.07	1.28	1.73
Persons employed in circular economy sectors	0.05	0.11	0.46	0.06	0.49	0.54
Patents related to recycling and secondary raw materials	0.47	1.35	1.35	0.36	0.97	0.24
Gross value added related to circular economy sectors	0.12	0.08	0.15	0.09	0.12	0.30
Gross investment in tangible goods in circular economy sectors	0.09	0.19	0.62	0.33	0.73	0.92

Table C2 Indicators of clusters in 2010

Indicators	*Cluster 1*	*Cluster 2*	*Cluster 3*	*Average*	*Cluster 1*	*Cluster 2*	*Cluster 3*
					Deviation from the average		
Generation of municipal waste per capita	513.5	598.28	471	504.35	1.814%	18.624%	–6.612%
Generation of waste, excluding major mineral waste per GDP unit	88.5	49	84.78	77.64	13.988%	–36.888%	9.196%
Generation of waste, excluding major mineral waste per domestic material consumption	23.45	9.3	9.22	11.27	108.075%	–17.480%	–18.190%
Recycling rate of municipal waste	52.15	51.53	16.22	28.92	80.325%	78.181%	–43.914%
Recycling rate of all waste, excluding major mineral waste	73	55.67	40.14	48.16	51.578%	15.594%	–16.653%
Recycling rate of packaging waste	76.85	73.27	54.01	61.4	25.163%	19.332%	–12.036%
Recycling rate of e–waste	29.1	44	21.66	27.51	5.780%	59.942%	–21.265%
Recycling of biowaste	118	120.66	13.56	51.43	129.438%	134.610%	–73.634%
Recovery rate of construction and demolition waste	58.5	87.37	56.67	63.51	–7.889%	37.569%	–10.770%
Circular material use rate	18.95	7.27	4.89	7.41	155.735%	–1.889%	–34.008%
Trade in recyclable raw materials (exports extra–EU28)	4,893,304	5,27,025.33	138,504.89	9,010,16.29	443.087%	–41.508%	–84.628%
Trade in recyclable raw materials (import extra–EU28)	353,192	365,585	53,127.33	162,948.93	116.750%	124.356%	–67.396%
Trade in recyclable raw materials (imports intra–EU28)	5,918,372.5	1,261,452	344,879.89	1,337,501.43	342.495%	–5.686%	–74.215%
Persons employed in circular economy sectors	1.18	1.41	2.81	2.28	–48.246%	–38.158%	23.246%
Patents related to recycling and secondary raw materials	0.9	0.55	0.73	0.72	25.000%	–23.611%	1.389%
Gross value added related to circular economy sectors	0.78	0.9	1	0.95	–17.895%	–5.263%	5.263%
Gross investment in tangible goods in circular economy sectors	0.15	0.09	0.27	0.22	–31.818%	–59.091%	22.727%

Table C3 Indicators of clusters in 2017

Indicator	*Cluster 1*	*Cluster 2*	*Cluster 3*	*Average*	*Cluster 1*	*Cluster 2*	*Cluster 3*
					Deviation from the average		
Generation of municipal waste per capita	462	507.89	548.67	510.07	–9.424%	–0.427%	7.568%
Generation of waste, excluding major mineral waste per GDP unit	76.79	62.61	63	64.72	18.650%	–3.260%	–2.658%
Generation of waste, excluding major mineral waste per domestic material consumption	25.82	8.35	8.08	10.79	139.296%	–22.614%	–25.116%
Recycling rate of municipal waste	54.25	44.12	17.67	39.9	35.965%	10.576%	–55.714%
Recycling rate of all waste, excluding major mineral waste	76.57	59.23	36.71	56.88	34.617%	4.132%	–35.461%
Recycling rate of packaging waste	80.95	67.52	50.43	65.78	23.062%	2.645%	–23.335%
Recycling rate of e-waste	40.35	43.78	24.96	39.26	2.776%	11.513%	–36.424%
Recycling of biowaste	113	83.44	15	73	54.795%	14.301%	–79.452%
Recovery rate of construction and demolition waste	68.68	91.19	59.35	81.15	–15.367%	12.372%	–26.864%
Circular material use rate	23.85	6.43	4.67	8.54	179.274%	–24.707%	–45.316%
Trade in recyclable raw materials (exports extra-EU28)	4,615,536	433,190.56	53,468.67	949,299.5	386.204%	–54.367%	–94.368%
Trade in recyclable raw materials (import extra-EU28)	40,639	104,872.44	4417.33	131313	235.564%	–20.136%	–96.636%
Trade in recyclable raw materials (imports intra-EU28)	6,413,417.5	677,090.67	138,782.33	1,381,214.14	364.332%	–50.979%	–89.952%
Persons employed in circular economy sectors	1.15	2.51	2.74	2.36	–51.271%	6.356%	16.102%
Patents related to recycling and secondary raw materials	1.14	0.9	0.73	0.9	26.667%	0.000%	–18.889%
Gross value added related to circular economy sectors	0.72	1	0.8	0.92	–21.739%	8.696%	–13.043%
Gross investment in tangible goods in circular economy sectors	0.13	0.25	0.24	0.23	–43.478%	8.696%	4.348%