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Leveraging the circular economy: Investment and innovation as drivers

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ABSTRACT

The circular economy plays a central role in Europe's new agenda for sustainable economic growth. Using Eurostat and United Nations data from 28 European countries pertaining to the years between 2011 and 2017 we identified two underlying dimensions of the circular economy — *environmental degradation* and *resource efficiency*. Then, using dynamic panel models we assessed the impact that investment, human capital, innovation, and previous circularity levels have on each dimension of the circular economy identified, comparing their impacts on both. Our substantive findings demonstrate that innovation and investment significantly reduce environmental degradation, whereas only investment is also significant in promoting resource efficiency. Furthermore, our study suggests that circular economy levels have an inter-annual dependence.

1. Introduction

In recent years pressing challenges such as natural resource depletion, environmental pollution, and climate change have led many economies to embark on a quest for strategies to balance growth and sustainability (United Nations Environment Programme, 2019). One solution that has been frequently pointed out is the transformation of the current linear economy into a more circular one. The key idea of the circular economy (CE) is to reduce waste and extend the useful lifetime of materials while preserving their value, for example, by using the by-products of certain economic activities as the input of others. It builds on the principle of efficiency and aims at reducing the consumption of raw materials and pollution.

Many countries and international organizations are developing strategies to boost the CE worldwide. China is one of the pioneers in recognizing CE adoption as a political concern, with the first regulatory action to support CE implementation — the "Cleaner Production Promotion Law" — appearing in 2003. By 2008, China had approved the "Circular Economy Promotion Law" which took effect in 2009. This law was set to foster the development of the CE, focusing on resource efficiency, protecting the environment, and sustainable development (Geng et al., 2012). Influenced by the Chinese CE implementation (Neves and Marques, 2022), the European Commission (EC) introduced its first CE Action Plan in 2015 (European Commission, 2015), and later the respective monitoring framework (European Commission, 2018), followed up by a new Action Plan in 2020 (European Commission, 2020). Circularity is set to continue as a pillar of the Cohesion Policy for the 2021–2027 period and is a priority for the European Regional Development Fund and Cohesion Fund (European Commission, 2019).

As a result of the increased overall awareness toward environmental issues and the ecological footprint of human (economic) activities, the CE is already considered "*an irreversible, global megatrend*" (European Commission, 2019, p. 10), and research about the topic has increased sharply (Merli et al., 2018). Although the CE is a practice-oriented concept, the research around the subject is predominantly theoretical, highlighting the need to expand quantitative analysis (Goyal et al., 2021). Furthermore, this growing popularity of the topic in the European Union (EU) seems not to have translated into implementation (Kirchherr et al., 2018; Kirchherr and van Santen, 2019).

To succeed, policy efforts need to be accompanied by adequate monitoring (Jacobi et al., 2018). In this sense, part of the earlier research on the CE is focused on measuring CE dimensions and levels (Saidani et al., 2019). While most authors use either a single variable or an *a priori* index as CE proxy (see, e.g., Elia et al., 2017; Halkos and Petrou, 2019; Mavi and Mavi, 2019; Sassanelli et al., 2019), a different approach has been used by Yang et al. (2011) and Yang et al. (2011) who use factor analysis to determine the weight of each variable in the index formation in a non-subjective manner. Nevertheless, there has not been a quantitative study measuring the CE across EU member countries and over time that separately measured the different key dimensions of the CE, even though several authors recognize that the CE is a multidimensional phenomenon (see e.g., de Jesus and Mendonça, 2018; Silvestri et al.,

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2020; Ünal and Shao, 2019). To bridge this gap, the first research question (RQ) we propose to answer is:

RQ1. What are the main underlying dimensions of the CE?

Further, policymakers need information on CE drivers to guide CE regulations and incentives (Neves and Marques, 2022). There exist some prior research on CE drivers (see e.g., de Jesus and Mendonça, 2018; Gusmerotti et al., 2019). However, there is no quantitative study focused on the macroeconomic drivers of the CE at the EU level in which the proxy used to measure the CE is more comprehensive than a single variable such as the GDP growth rate (Armeanu et al., 2017), resource productivity (Robaina et al., 2020) or circular material use rate (Neves and Marques, 2022). To the best of our knowledge, no study in the existing literature applies factor analysis to measure the CE in its different dimensions and determines the macroeconomic drivers for each. In this sense, the second RQ we intend to answer with this work is:

RQ2. What are the potential macroeconomic drivers of the CE, and how do these drivers affect each CE dimension?

One particular driver of the CE might be the past levels of CE, given that in a CE a virtuous circle can be established, in which waste materials are transformed into resources to create a closed-loop system (Herczeg et al., 2018), and the increasing stock of knowledge on circularity (De los Rios and Charnley, 2017) will allow to further promote the CE. Hence, the last RQ that this work aims to answer is:

RQ3. Are CE levels of a given period built over past levels?

We thus add to the normative literature by providing the first quantitative study that comprehensively examines the CE, assessing its dimensions and the drivers of each across six years. We argue that this is relevant for the CE body of research because it seems plausible that each of the CE drivers may have a distinct impact on each of the different CE dimensions.

The remainder of this work is organized as follows. Section 2 presents the literature review, while Section 3 includes the framework for assessing the CE dimensions and drivers. The results are shown in Section 4, and in Section 5 we present the discussion and implications. Finally, Section 6 includes the conclusions and limitations.

2. Theoretical background

2.1. The concept of circular economy

There is no consensus regarding the origin of the CE. Some authors attribute it to China (Liu et al., 2009), while others argue that the term first appeared in western literature (Pearce and Turner, 1990). Coincidentally, there is also no consensus regarding a standard definition (Kirchherr et al., 2018). CE as a phenomenon has gained growing attention in the last years, primarily driven by policy-makers and business practitioners, and this eventually led to greater academic attention. (Merli et al., 2018). With this growing attention, distinct views and definitions of the CE have also emerged. The European Commission (2015, p. 2) defines the CE as a system "*where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized*". Going further in terms of how to achieve this, Geissdoerfer et al. (2017, p. 759) include in their definition that in a CE, "*resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops (…) through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling*". Other definitions such as the one given by Murray et al. (2017, p. 25) adopt a broader perspective, including aspects of sustainability, profiling the CE as "*an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being*".

We searched the literature for CE definitions published in conceptualized journals, finding that different definitions comprehend different dimensions of the CE. The overarching concepts were economic prosperity, environmental sustainability, human well-being, recycling, reducing resource consumption, reusing, reducing emissions, reducing waste, resource efficiency, and energy efficiency. The definitions we selected and their correspondence with the dominating concepts identified are in Table 1.

The lack of a universally accepted CE definition leads us to provide a comprehensive definition of the concept that our work will draw on. Based on the interpretation of our extensive literature review, we propose the following definition:

A circular economy is an economic system that steers economic growth toward sustainability by redesigning production and consumption patterns to promote resource and energy efficiency while preventing environmental degradation.

2.2. Earlier research on circular economy

The literature review presented in this subsection was performed by searching the Web of Science and Scopus databases for the most recent review articles focused on CE (from the last five years) from the top-ranked journals (ABS 3 and 4 or 1st Quartile in Scimago). Reading the review papers thus detected led us to select approximately 230 articles whose abstracts were screened. Of these, we fully read about 70 articles, the most important of which are cited in the paragraphs below.

Our revision of the relevant literature underscores that the CE has been gaining interest from researchers, as pointed out by Merli et al. (2018). Some are focused on exploring the concept and its applications by reviewing existing literature (Merli et al., 2018; Murray et al., 2017), while others carry out empirical analyses of CE levels and drivers.

A plethora of indicators exists for measuring circularity (Saidani et al., 2019). Authors such as Elia et al. (2017) gathered some of them to propose a taxonomy of index-based methodologies for measuring CE adoption. In their consideration of indicators that can measure the CE, ranging from multiple indicator methods like material flow analysis (MFA) and life cycle assessment (LCA) to single indicator methods like the carbon footprint, the authors conclude that all of them have some shortcomings. The main criticisms are that single indicators are too narrow in scope and composite indicators lack accuracy. Moraga et al. (2019) also developed a framework to categorize indicators. They concluded that to measure the CE level, a set of indicators is a better choice than a single indicator because the concept of CE comprises

Table 1
Dimensions included in different CE definitions.

Authors	EP	ES	H	RC	RD	RE	RW	E	RU
de Jesus et al. (2019)	X	X	X	X	X		X	X	X
European Commission (2015)	X	X		X		X	X	X	X
Geissdoerfer et al. (2017)				X	X	X	X	X	X
Murray et al. (2017)		X	X						
Suárez-Eiroa et al. (2019)		X		X	X	X	X		X
Kirchherr et al. (2017)	X	X	X	X	X				X
Ellen MacArthur Foundation (2012)				X		X	X		X
Burger et al. (2019)				X	X			X	X
Liu et al. (2009)	X	X		X	X		X	X	X
Fang et al. (2007, p. 316)	X	X	X	X				X	
Elia et al. (2017)	X			X	X	X	X		X

Note: EP - Economic prosperity; ES - Environmental sustainability; H - Human well-being; RC - Recycle, RD - Reduce; RE - Reduce emissions; RW - Reduce waste; E – Resource/Energy efficiency; RU - Reuse.

several dimensions that are difficult to capture at once. However, none of the indicators found in the literature summarizes the different circularity dimensions while measuring them individually at the macro level. This study addresses this shortcoming by developing an indicator that measures the CE in its different dimensions — environmental degradation and resource efficiency — building it with data available for all the European union member countries over multiple years. Moreover, we propose to use factor analysis to determine the main CE dimensions. These will thus emerge from the data, limiting the risk of biased weighting (De Pascale et al., 2021).

Several studies have analysed the CE using quantitative techniques. Halkos and Petrou (2019), for example, assessed the EU member states' environmental efficiency levels, concluding that countries that are more environmentally efficient present higher recycling rates. Another example is the analysis of Mavi and Mavi (2019), who analysed how the member countries of the Organisation for Economic Co-operation and Development (OECD) performed in terms of energy and environmental efficiency between 2012 and 2015. These authors found a strong relationship between energy use and greenhouse gas (GhG) emissions. Škrinjarí (2020) ranked several European countries in their circularity, elaborating on how factors such as gross domestic product (GDP) per capita, education, and the development of R&D could have better CE performance — but not testing these proposed drivers on empirical data.

On the contrary, Armeanu et al. (2017) investigated the drivers of sustainable economic growth in the European Union member countries, resorting to longitudinal data regression models. However, the authors used the real GDP growth rate as the dependent variable, which does not necessarily reflect the development of the CE. Other authors such as Robaina et al. (2020) and Neves and Marques (2022) also used a single variable as a proxy to measure the CE while studying CE drivers. Ranta, Aarikka-Stenroos, Ritala and Mäkinen (2018) studied institutional drivers and barriers for China, the US, and Europe using a framework of regulative, normative, and cultural-cognitive institutional pillars and case studies, not covering economic drivers. Charef and Lu (2021) identified the CE drivers but only for the construction sector specifically. Analysing the literature, it becomes evident that there is no quantitative study focused on the macroeconomic drivers of each of the leading CE dimensions at the EU level.

In summary, it is noticeable while surveying the literature that CE is still a novel and thus undefined concept, subject to different interpretations and measures; and that there is no consensus regarding its main macroeconomic drivers. Thus, this work aims to fill the gap in the literature by using longitudinal econometric models to determine how each circularity dimension is affected by investment, human capital, innovation, and previous levels of the respective circularity dimension for the EU-27 plus the United Kingdom.

3. Framework

As the main objectives of this study are to (i) identify and measure the main underlying CE dimensions; (ii) assess the drivers of each; and (iii) address each of these longitudinally, we resorted to factor analysis and dynamic panel models. Factor analysis will enable us to capture the main dimensions of CE, using as a basis a comprehensive set of CE-related indicators, which need to be chosen carefully. Each dimension will be used as the dependent variable in a specific dynamic panel model, in which the independent variables will also be chosen considering earlier research. The rationale behind the choice of the variables used to identify the CE dimensions is presented in Subsection 3.1, whereas the reasoning behind the methodology for assessing the CE drivers is provided in Subsection 3.2 (the research flow can be seen in Fig. 1).

3.1. Circular economy dimensions

Because of the growing popularity of the CE, the problem of how to measure it has been gaining attention (Sassanelli et al., 2019). Nonetheless, measuring the circularity levels is still a task limited by several constraints. The first has to do with the lack of a standardized definition for the CE, as discussed in Section 2. The second arises from data availability. There is a clear trade-off between countries, years, and variables that can be included. Hence, if one favours the comprehensiveness of the CE over the representativity of countries, conclusions will be affected in terms of generality. Otherwise, conclusions may disguise essential aspects of the CE. This limitation led to the development and use of *a priori* composite indices, which summarize complex and multidimensional phenomena and are easy to interpret (OECD, 2008), for example, the circular economy efficiency index introduced by Ma et al. (2014).

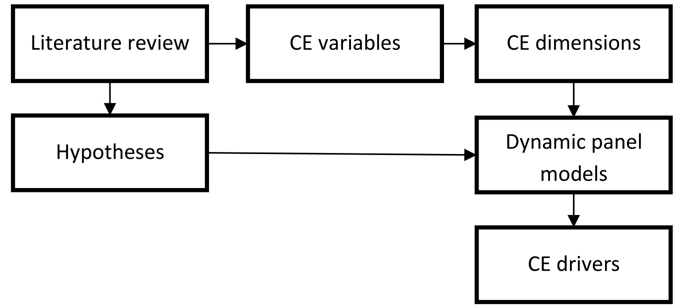

Fig. 1. Research flowchart.

Nonetheless, composite indices may oversimplify complex phenomena, reducing them to a single number. Each variable's weight in the index formation is defined in an *a priori* subjective manner and not based on the actual data (Cruz-Jesus et al., 2012). For these reasons we use original CE-related variables on which we perform a factor analysis, which allows measuring the CE as a multidimensional phenomenon, allowing us to identify the different dimensions through which the CE develops. This is an approach that other authors have used (Yang et al., 2011; Yang et al., 2011). Each extracted factor is an underlying dimension of the CE, which are orthogonal to each other.

To choose the variables for inclusion in the factor analysis we considered that the CE aims to maximize economic growth while minimizing environmental degradation, waste, and undesired generated output and emphasizing productive efficiency and resource reuse. The variable of resource productivity addresses productive efficiency and energy productivity, which express the amount of desired economic output, GDP, produced for each raw material and energy unit. A higher value of resource productivity indicates higher levels of circularity (European Environment Agency, 2016; Magnier, 2017; Tantau et al., 2018). Several studies assume the same relationship regarding energy productivity (see, e.g., Bassi and Dias, 2019; Geng et al., 2012; Mavi and Mavi, 2019). The undesired generated output is measured by pollution and waste. Hence, we used the amount of waste generated per GDP unit. A lower level of the variable reflects a higher level of circularity (see, e.g., Geng et al., 2012; Halkos and Petrou, 2019; Mavi and Mavi, 2019). To address the amount of pollution we resorted to GhG per GDP unit. As with the variable waste, lower levels indicate higher circularity (see, e.g., Halkos and Petrou, 2019; Jacobi et al., 2018; Mavi and Mavi, 2019). Finally, resource reuse is measured by two variables. First, we assess how much of the generated waste is fed back into the economic system as secondary materials, using the recycling rate of municipal waste, which has been extensively employed in measuring the CE (see, e.g., Geng et al., 2012; Halkos and Petrou, 2019; Mavi and Mavi, 2019) with a higher recycling rate indicating higher circularity. Second, it is also essential to consider how much of the material input needs are covered by those secondary materials instead of raw materials. For this we added the circular material use rate, which many studies consider to be a critical indicator of circularity (see, e.g., Gusmerotti et al., 2019; Jacobi et al., 2018; Mayer et al., 2018; Tantau et al., 2018). The European

Environment Agency (2016) also includes the circular material use rate in its list of indicators to measure circularity.

The variables were selected based on an extensive literature review and obtained from the Eurostat database. As one of the main statistical authorities in Europe, Eurostat produces highly reliable and harmonized publicly available statistics, thereby allowing other researchers to reproduce our results. The respective acronym, description, and theoretical support of each variable used are in Table 2. Each variable exists for the years between 2011 and 2017 for each EU-28 country.

3.2. Circular economy drivers

This subsection deals with the formulation of the hypotheses, the description and justification of the variables used, and the econometric models' specifications.

3.2.1. Hypotheses

The CE is a type of economic system, a way of conducting economic activity. It is therefore expected that some of the drivers of economic growth, in general, might be important to stimulate the CE when directed toward circularity. Bearing this in mind, we searched for the main drivers of economic growth in the economic literature that could apply to the CE.

Many growth theories (see, e.g., Barro & Sala-i-Martin, 2004; Romer, 1990; Solow, 1956) assume a positive relationship between the GDP of a given period and the GDP of the previous period. The same could apply to the CE, given that the transition to a CE requires profound changes to the production process and goods produced (see, e.g., Edmondson et al., 2019; Ghisellini et al., 2016; Merli et al., 2018), which calls upon companies to explore new terrain. This exercise of exploration can lead to economies of learning, as the novelty factor gradually decreases. Experience helps crystalize the best approaches, and this can already be seen in studies such as De los Rios and Charnley (2017).

We included the lagged dependent variable, with a lag of one year to measure the inter-annual dependence of CE. Given the above, we formulate the following hypothesis:

H1. The CE level of a given year builds over the CE level of the previous year, translating into an inter-annual dependence of the CE.

One of the most widely accepted variables in economic growth models is accumulated capital stock (see, e.g., Kaldor, 1957; Romer, 1990; Solow, 1956), which results from the savings of each period and allows the maintenance and expansion of the production process. The accumulated stock of fixed capital, and thus fixed capital formation, can be considered essential for the development of the economic activity, so investment directed toward circular activities should leverage the CE. For instance, the recycling sector in developed economies is relatively capital-intensive (Yusuf et al., 2000). Thus, an increase in fixed capital in this sector, in other words, investment, can significantly impact its productivity.

To measure investment in circular activities, we used the gross investment in tangible goods in the recycling, repair, reuse, and rental and leasing sectors, and likewise many studies on economic growth (Barro, 1991; Moral-Benito, 2012). We considered the value as a percentage of GDP. Although we recognize that this variable does not capture all the investment that can contribute to circularity, we believe it serves as the best proxy given the available data. From this, we hypothesize:

H2. Investment in circular activities, as a percentage of GDP, is positively associated with higher levels of CE.

Another frequently identified driver of economic growth is technological progress related to innovation (Kaldor, 1957; Romer, 1990; Solow, 1956). There is a need to maximize efficiency and redesign products to facilitate recycling and increase durability (Ellen MacArthur Foundation, 2015). Therefore, a circular system must constantly incorporate state-of-the-art technologies and dedicate resources to transition to progressively circular products. There is evidence in the literature that the CE demands innovation. For example, Pitkänen et al. (2016) find technological development and R&D to be critical factors in achieving a green economy. This aligns with the considerations of the European Environment Agency (2014) on innovation being a relevant factor behind resource productivity, a vital circularity indicator.

Innovation can be assessed by several variables, such as the number of patents or the ratio of R&D over GDP (Cainelli et al., 2020). However, not all inventions and innovations are patented, due either to their nature or to the inconveniences of the patenting process. Furthermore, there might be differences among national patent offices that can lead to discrepancies between countries regarding the incentives of pursuing a patent (Archibugi, 1992). We, therefore, prefer to use R&D data, specifically total government budget appropriations or outlays on R&D, as a percentage of total general government expenditure. This arises from the fact that government subsidies for R&D are more often directed at projects that, although promising high returns for the general public, present insufficient private returns to be pursued by private investors due to the existence of externalities (Jaffe et al., 2005). Regarding innovation, we hypothesize:

H3. Innovation is positively associated with CE.

A third feature often identified as a driver of economic growth is human capital. Human capital is essential to develop R&D activities and ultimately enable innovation (Romer, 1990). Barro (1991) confirms the existence of a positive relationship between human capital and economic activity, and literature shows that human capital has an indirect impact on economic activity by contributing to better policies (Glaeser et al., 2004) and improving a variety of indicators such as civic participation and environmental conditions (Sianesi and Van Reenen, 2003). Yao, Ivanovski, Inekwe and Smyth (2019) found that human capital can positively affect circularity because it reduces aggregate energy consumption and promotes a transition from dirty to clean energy.

In order to measure the stock of human capital of each country, we considered the average years of schooling of persons aged 25 and older, which is a well-established proxy of human capital (as mentioned in Teixeira and Queirós, 2016). The multiple ways through which human capital can nurture economic activity and shift it toward a cleaner path leads us to hypothesize that:

H4. Countries with a higher stock of human capital reach higher levels of circularity.

Lastly, we considered the impact that growth itself might have on the CE. The main appeal of the CE is to reconcile economic prosperity and environmental sustainability, which implies that economic growth has a negative impact on circularity. Nevertheless, a vast repository of literature supports the belief that economic growth is a crucial element of human development (Ranis et al., 2000). The Environmental Kuznets Curve (EKC), discovered in the 1990s (see, e.g., Grossman and Krueger, 1995), states that a rise in GDP per capita increases environmental degradation up to a certain point, after which it diminishes it. Hence, we included the growth rate of the real GDP as a control variable.

3.2.2. Models' specification

We next specify the models to test the hypotheses defined above. As previously stated, the factor analysis might indicate more than one underlying dimension to the CE, and thus several econometric models might be estimated, one for each of the underlying dimensions of the dependent variables. Nevertheless, for reliability, we always considered the same set of covariates in all specifications. By so doing, we will be able to understand in greater depth not only if the hypotheses are true but how each variable influences the CE in its various spheres, instead of merely capturing the overall effect. The independent variables were gathered from the Eurostat and United Nations Human Development Database for the years between 2011 and 2017. The general model specification is the following:

Table 2
CE variables used in the factor analysis.

Variable	Description	Support
Waste	Generation of waste excluding major mineral waste per GDP unit.	Geng et al. (2012); Mavi and Mavi (2019); Halkos and Petrou (2019)
Recycling	Recycling rate of municipal waste.	Tantau et al. (2018); Halkos and Petrou (2019); García-Barragán et al. (2019)
Use Rate	Circular material usage in the percentage of total material use.	Tantau et al. (2018); Jacobi et al. (2018); Mayer et al. (2018); Gusmerotti et al. (2019); European Environment Agency (2016)
GhG	Human-made emissions of the 'Kyoto basket' of GhG in percentage of the GDP.	Halkos and Petrou (2019); Mavi and Mavi (2019); Jacobi et al. (2018)
Energy Productivity	GDP, in purchasing power standard (PPS), per unit of gross available energy for a given calendar year, in kg of oil equivalent.	Mavi and Mavi (2019); Bassi and Dias (2019); Geng et al. (2012)
Resource Productivity	GDP, in PPS, generated per unit of domestic material consumption.	Tantau et al. (2018); European Environment Agency (2016); Magnier (2017)

$$y_{i,t} = \alpha y_{i,t-1} + \beta_1 circ_{invest\,i,t-1} + \beta_2 circ_{invest\,i,t-2} + \beta_3 gov_{rd\,i,t-1} + \beta_4 gov_{rd\,i,t-2} + \beta_5 gov_{rd\,i,t-3} + \beta_6 school_{avg\,i,t-1} + \beta_7 growth_{i,\,t-1} + u_{i,t}$$

$$u_{i,t} = \lambda_t + \mu_i + \varepsilon_{i,t}$$

where for the i-th country observed in period t, $y_{i,t}$ denotes the dependent variable, which will be the CE dimensions found in the factor analysis, $growth_{it}$ is the real GDP growth rate as annual percentual change on the previous year, $circ_{invest_{it}}$ is the percentage of GDP spent on gross investment in tangible goods for related circular activities, $gov_{rd_{it}}$ is the total government budget appropriations or outlays on R&D as a percentage of total general government expenditure, $school_{avg_{it}}$ is the average years of schooling, λ_t represents the unobservable year-specific effect, μ_i denotes the unobservable country-specific effect, and $\varepsilon_{i,t}$ is the remainder stochastic disturbance term. The lag structure is deemed appropriate for each variable, being at least one year to detect the causal relationship between the independent and the dependent variables in a context of dynamic effects.[1]

Given our hypotheses that CE levels are persistent over time and that the panel data structure consists of observations for different countries and different years, we use dynamic panel data model estimation. When considering a dynamic panel specification, the lagged value of the explained variable is correlated with the error terms, resulting in endogenous regressors (Nickell, 1981), meaning that neither the fixed effect nor random effect panel estimators will be consistent. As a solution, we use the system generalized method of moments (GMM) estimation method (Blundell and Bond, 1998), which enables us to deal with the endogeneity problem while being less prone to bias and the problem of weak instruments than using the GMM estimator of Arellano and Bond (1991) (AB methodology). The AB methodology can neutralize the individual fixed effects by resorting to the first differences of the original model. For this, the levels of the lagged variables are used as instrumental variables, which are needed to derive the moment conditions. What distinguishes the system-GMM from the AB methodology is that a system of equations is considered to explore more moment conditions: a level equation (with lagged differences as instruments) is considered in addition to the differences equation (with lagged levels as instruments).

The model can be estimated in one or two steps, depending on the choice of the weighting matrix (see, e.g., Baltagi, 2008). Due to our data span, a robust first step GMM estimator was considered to be adequate. Another option is whether to use fixed effects. We opt to use time-fixed effects as considered relevant. For the system-GMM estimation to be consistent, the disturbance term should have no autocorrelation. For lagged endogenous variables and weak exogenous variables to be valid as instruments, the transient disturbances in the base model should be non-serial correlated (Arellano and Bond, 1991). Hence, the differenced disturbances evolve following an AR(1) process and, by construction, exhibit first-order serial correlation. However, if the disturbances do not present a second-order serial correlation, no serial correlation exists in the original equation (Blundell and Bond, 1998). This conjecture can be tested with the Arellano–Bond test for second-order (AR(2)) serial correlation in the first-differenced residuals (Arellano and Bond, 1991).

The validity of the overidentifying moment conditions can be directly tested by the Sargan test, given that we considered the optimal (robust) first step GMM. Since the null hypothesis is that additional instruments are jointly uncorrelated with the error term, the instruments are not valid if rejected.

4. Results

This section presents the results of the factor analysis and the subsequent estimation of the dynamic panel models. It shows how the factor analysis resulted in two factors, identifying two underlying dimensions of the CE. These dimensions were then used as dependent variables in the econometric models to test the hypotheses defined in Subsection 2.2.

4.1. Factor analysis

The data suitability for factor analysis was assessed through the Kaiser–Mayer–Olkin measure, which returned the value of 0.58, which is above the threshold of 0.5 (Kaiser, 1974). The next step was to decide how many factors we would extract. According to the Kaiser, Pearson, and Scree-Plot criteria, the optimal number of factors is two (see Table A1 in the Appendix). The two factors were subsequentially interpreted using the factors' loadings, shown in Table 3. Considering the correlation between the six original CE-related variables and the two factors, we labelled them as environmental degradation and resource efficiency.

Environmental degradation comprises the opposite of the designated purpose of a CE. This dimension is defined by indicators that signal a low level of circularity; more specifically, the level of waste generation,

Table 3
Factor loadings.

	Environmental degradation	Resource efficiency
Waste	**0.87**	−0.13
GhG	**0.85**	−0.31
Energy Productivity	**−0.76**	−0.01
Use Rate	0.18	**0.94**
Resource Productivity	−0.44	**0.76**
Recycling	−0.25	**0.74**
Variance (%)	50%	25%
Variance Total	50%	75%

[1] The lag structure for $circ\_invest_{it}$ and gov_rd_{it} is based on our conviction that both need a longer time span until results are obtained. The latter, gov_rd_{it}, is potentially the slowest given that R&D projects are usually time consuming (Mansfield et al., 1971; Wang and Hagedoorn, 2014). Investments in fixed capital might need more than one period to produce outcomes, depending on the size and complexity of the capital goods needed. For example, the construction of a new recycling plant might need more than a year to be completed.

energy consumption, and pollution, given that the *modus operandi* of a circular economy should envisage the reduction of material and energy consumption and thus the generation of waste while cutting emissions (European Environment Agency, 2016). Furthermore, as the level of emissions is closely related to the level of energy consumption (Mavi and Mavi, 2019), it makes sense not only that energy productivity is more related to environmental degradation than to resource efficiency, but also that the relationship it has with the factor is negative, meaning that environmental degradation results from a low level of energy productivity.

Resource efficiency captures the other aspect of the core idea of the CE as defined in Subsection 2.1, because resource productivity, circular material use rate, and recycling rate convey the need of maximizing the economic value of resources. Higher levels of recycling, resource productivity, and circular use rate boost resource efficiency by demanding fewer raw material inputs for the same output in terms of GDP, or, in other words, allowing for higher outputs with the same number of inputs.

4.2. Dynamic panel models

Since two dimensions were found in Subsection 4.1, two econometric models have been estimated, one with environmental degradation as the dependent variable and one with resource efficiency. The dynamic panel data estimation for the coefficients of each variable for both models is reported in Table 4. We do not reject the AR(2) null hypothesis for either model, so no serial correlation is detected. The Sargan test for the validity of the over-identifying moment conditions suggests the appositeness of instruments — we fail to reject their exogeneity in the case of both models. Given these results, we assert that we have no evidence of misspecification, namely inconsistency problems due to weak instrumentation.

It is important now to make some comments on the model estimates. First, economic growth is significant ($p < 0.01$) in the first model, having a positive impact on environmental degradation and thus a negative impact on circularity. Investment in the circular activities is significant in both models ($p < 0.1$), having a considerable effect on mitigating environmental degradation and an even greater impact on improving resource efficiency, thus having an overall positive impact on CE, confirming our first hypothesis. The lagged dependent variable is significant in both models ($p < 0.01$), confirming the second hypothesis and showing the CE's inter-annual dependence. Moreover, time persistence is vital, as the coefficient in both models is positive and high. Government expenditure on R&D has a positive effect on mitigating environmental degradation ($p < 0.05$), but only after two years. While not affecting resource efficiency, it positively impacts the overall circularity levels, confirming the third hypothesis. Finally, human capital does not significantly affect environmental degradation or resource efficiency, so the fourth hypothesis is not confirmed.

Table 4
Dynamic panel data estimation of the relationship between the CE, investment, innovation, and human capital (dependent variable of model I is environmental degradation and of model II is resource efficiency).

	Lag	Environmental degradation			Resource efficiency		
env_deg	1	0.94	***	(0.07)			(0.01)
res_ef	1				0.99	***	(0.01)
circ_invest	1	0.59		(0.88)	1.93	*	(0.97)
circ_invest	2	−1.17	**	(0.60)	−0.60		(0.17)
gov_rd	1	−0.08		(0.10)	−0.08		(0.13)
gov_rd	2	−0.13	**	(0.05)	−0.08		(0.12)
gov_rd	3	0.07		(0.05)	−0.01		(0.01)
school_avg	1	0.01		(0.02)	0.01		(0.08)
growth	1	0.03	***	(0.01)	0.01		(1.17)
Number of observations				127			**127**
Number of instruments[a]				21			**21**
AR(2) p-value				0.56			0.84
Sargan p-value				0.52			0.52

Note: Standard deviations in parentheses; ***, **, and * denote statistical significance at the 1%, 5%, and 10% level.

[a] These results are obtained with a collapsed instrument matrix as in Roodman (2009).

5. Discussion

5.1. Discussion of findings

Our search for the CE's underlying dimensions conducted through factor analysis resulted in the identification of two: resource efficiency, which the CE aims to increase (Cainelli et al., 2020; Ncube et al., 2021); and environmental degradation, which the CE aims to reduce (Nobre and Tavares, 2021). It is worth mentioning that these dimensions are orthogonal to (i.e., independent of) each other, meaning that one country can perform relatively well in one and poor in the other. This is a crucial finding of our study: CE is a multidimensional phenomenon and should, therefore, be considered as such. In addition to determining the underlying dimensions of the CE, we also wanted to assess the drivers of each one independently. For this, we developed a set of hypotheses that were subsequently tested using dynamic panel models.

Our results point to an inter-annual dependence of the CE since, on both dimensions (models) the lagged dependent variable has a positive impact. Moreover, the time persistence is strong, as the coefficient in both models is positive and high. Several factors can explain this effect. For instance, there is evidence that CE-related activities are being progressively adopted by companies, usually starting with those that have the lowest index of circularity, such as waste recycling and treatment (Aranda-Usón et al., 2020). Furthermore, companies seeking to adopt circular processes can take advantage of the growing scientific and practical knowledge regarding CE practices (Moktadir et al., 2018). Moreover, considerable synergies can arise between circular companies regarding material and energy use (Domenech et al., 2019). Lastly, adopting certain circular practices could encourage others to do the same. For example, an increase in recycling allows for a higher proportion of secondary materials to be incorporated into the production of new goods (Tallentire and Steubing, 2020).

Notably, even though environmental degradation builds on the previous year's values, the impact of the drivers that mitigate it is felt only after two years, which indicates that countering environmental degradation requires solid and continuous effort.

We found evidence that investment in circular activities is strongly associated with high CE levels. This type of investment affects the CE on both dimensions simultaneously — reducing environmental degradation and promoting resource efficiency. It is interesting to note that the impact on the environment takes longer to be felt (two years instead of just one, as is the case of resource efficiency). This might indicate that an increase in resource efficiency could help to mitigate future environmental degradation. For example, increasing recycling rates and the material use rate can lead to a reduction in the need for energy use to produce goods as well as a reduction in GhG emissions that are linked to the disposal or transportation of certain materials (see, e.g., Yousef et al., 2020; Zhang et al., 2018).

Note, however, that higher levels of innovation positively impact the reduction of environmental degradation but have no effect on resource efficiency. This result might derive from the fact that public environmental and energy R&D has been primarily directed towards energy-related activities (Garrido-Prada et al., 2021), thus being more prone to reduce environmental degradation than promoting resource efficiency, which aligns with the strong European commitment to reduce greenhouse gas emissions (European Comission, 2020).

It was with some surprise that we found no evidence that an increase in human capital positively affects CE levels. However, as pointed out by

Burger et al. (2019), the skills demanded by the CE do not translate solely into educational attainments since there is a need for specific skills and on-the-job training. These authors state that the education level requirements of the CE are very heterogenous and do not differ much from the rest of the economy, which is still predominantly linear. Thus, an increase in human capital does not necessarily affect the circular sector and might mainly be absorbed by non-circular activities, which could explain our result.

Finally, economic growth is negatively associated with circularity, which is precisely the problem of the linear economy that the CE tries to tackle (Lieder and Rashid, 2016), revealing that the current paradigm is still predominantly linear (Merli et al., 2018). In summary, the higher the linear economy, the lower is the circular one.

5.2. Implications

Our results make some positive contributions to science and have important implications for legislators and decision-makers.

A crucial finding of our study is that CE is a multidimensional phenomenon. We argue that future research and policy-making in the context of CE should at the very least start from the assumption that CE cannot be reduced to a single dimension or aspect, as our results point out.

The two dimensions of the CE that we identified — environmental degradation and resource efficiency — are aligned with the often-adopted CE definition that focuses on the technological cycle of resources, which also underlies the European "CE monitoring framework" (Moraga et al., 2019). If the necessary data are publicly available, our framework could help policy-makers monitor the evolution of the environmental degradation and resource efficiency of EU-member countries and thus better evaluate the effects of policies or funding.

Policy efforts can play an essential role in providing a sound foundation for the transition to a sustainable system, given that the CE has a positive inter-annual dependence. Promoting higher circularity levels at any given time will positively impact future circularity levels. Because of this positive dynamic, post COVID-19 recovery plans that incorporate CE incentives, such as advised by Sharma et al. (2021), will hold long-term benefits.

Notably, circular investment has a strong positive impact on the CE, which is in line with earlier studies such as de Jesus and Mendonça (2018), who found that the unavailability of cost-efficient technology is one of the main barriers to the transition to a CE. Therefore, investment should be a focal point of decision-makers to drive the CE. Governments can promote CE practices, for example, by easing the access to funding for SMEs, which are especially active in fields such as recycling, repair, and innovation (European Commission, 2015). SMEs are not only key actors in CE implementation (Prieto-Sandoval et al., 2019) but are also at a disadvantage compared to large companies whenever CE implementation requires large investments in tangible goods. They generally have fewer resources (Bassi and Dias, 2019). Additionally, as Kirchherr et al. (2018) suggested, fiscal incentives could also promote investment in circular activities (regardless of the company size).

Our models corroborate the notion that innovation is an essential enabler of the CE (see, e.g., de Jesus et al., 2019; European Commission, 2015; Konietzko et al., 2020; Prieto-Sandoval et al., 2018), having a particular benefit in terms of reducing environmental degradation, confirming what various authors such as Puertas and Marti (2021) have found. These findings are also concordant with Garrido-Prada et al. (2021), who found that public environmental and energy R&D has a positive impact on the available knowledge on environmental and energy topics and thus on the potential implementation of CE activities by SMEs. Given our findings and the literature cited, we argue that policy-makers should increase the share of government expenditure dedicated to R&D, particularly environmental and energy R&D. European funding has already had great importance in supporting research and innovation projects under the InnovFin program, such as the loans given to Gorenje for R&D activities to produce greener domestic appliances (European Investment Bank, 2015).

Human capital was not found to affect CE levels, which contradicts the findings reported in earlier studies of a positive link between human capital and circular practices (see e.g., Ulucak and Bilgili, 2018; Yao et al., 2019). Furthermore, our findings neither corroborate nor contradict studies that point to either a positive association between higher education levels and a more robust environmental consciousness (Neves and Marques, 2022; Zsóka et al., 2013) or a negative one (Sánchez-Llorens et al., 2019). Nevertheless, as de Jesus and Mendonça (2018) point out, providing adequate education and training could play an essential role in the CE's environmental awareness and skill base. However, for this, our empirical analysis suggests that increasing the average school years is not enough. In this sense, to improve environmental conscientiousness, policy-makers should promote specific education about environmental issues, which has been pointed out as an essential action to promote circularity (Zsóka et al., 2013).

Another finding is that economic growth is negatively associated with circularity, which is precisely the problem of the linear economy that the CE tries to tackle (Lieder and Rashid, 2016), revealing that the current paradigm is still predominantly linear (Merli et al., 2018). In summary, the higher the linear economy, the lower is the circular one, which is in line with the findings of Neves and Marques (2022), who gave a possible explanation that higher purchasing power could lead to a preference for new products over reused or containing recycled material ones.

In summary, our study shows (1) that the CE comprises two dimensions — environmental degradation as an issue it intends to resolve and resource efficiency as its main target — while providing a framework to measure both, and (2) that policy-makers can promote the CE, in particular, the environmental sustainability aspect, by further financing R&D activities and investment into circular activities. Circular investment should assume a central position given its potential to mitigate environmental degradation and improve resource efficiency. These findings are a valuable insight for policy-makers in directing efforts and funds to achieve a more circular European economy.

6. Conclusions and limitations

For the CE to succeed its objectives must be clearly defined, mechanisms understood, and progress measured. Our study contributes to the literature in three ways. First, we propose a new comprehensive definition of CE derived from the existing practices and ideas about the concept. Second, we present a framework for measuring the CE at the macro-level that distinguishes its two key areas, environmental degradation, and resource efficiency, providing deeper insights into the performance of countries regarding the CE than a single indicator or index could. Third, this work highlights the importance of investment and innovation for the CE and its inter-annual dependence, which indicates that the benefits of promoting circularity will propagate over time, meaning that policy efforts can have an essential role in providing a sound foundation for the transition to a sustainable system.

A key finding is the pronounced importance of investment for circularity, increasing resource efficiency, and mitigating environmental degradation. Another important finding is that innovation has a positive effect on circularity by lessening environmental degradation.

Like any other study, we need to acknowledge some limitations. One is that some important aspects of the CE are not highlighted. Green logistics (de Souza et al., 2022; Seroka-Stolka and Ociepa-Kubicka, 2019) and sustainable supply chain management (Allen et al., 2021; Genovese et al., 2017; Manavalan and Jayakrishna, 2019) are key to the CE and more efforts should be devoted to these topics. Another limitation is that we were unable to establish a relationship between human capital and the CE. The proxy we used to measure human capital, average years of schooling, could lack important information. It omits skills gained through non-formal education, such as on-the-job training, which is essential for several CE activities, and the quality of schooling. We find that future studies that aim to study the relationship between human capital and the CE should include measures that assess the specific CE-skills of the workforce and the level of environmental education. Also, the second CE dimension, resource efficiency, was not as well explained by our model as the first one. This fact makes us wonder if we are omitting some key drivers or if this second dimension is to some extent more complex than the first. Finally, although this is to the best of the authors' knowledge one of the first comprehensive studies examining the CE dimensions and drivers across different years, we need to acknowledge that the period examined could be longer if more recent data were available. In this sense, we urge future researchers to include more extended periods in this research topic.

CRediT authorship contribution statement

Carlotta Lehmann: Conceptualization, Data curation, Formal analysis, Writing – original draft, Conception and design of the study, Collection of data, Analysis and interpretation of data, Drafting the manuscript. **Frederico Cruz-Jesus:** Conceptualization, Data curation, Formal analysis, Conception and design of the study, Analysis and interpretation of data, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Tiago Oliveira:** Conceptualization, Conception and design of the study, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Bruno Damásio:** Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published.

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.

Appendix

Table A.1
Eigenvalues of the correlation matrix.

Factor	Eigenvalue	Difference	Proportion	Cumulative
1	2.95	1.43	0.49	0.49
2	1.52	0.83	0.25	0.75
3	0.69	0.17	0.11	0.86
4	0.52	0.33	0.09	0.95
5	0.19	0.06	0.03	0.98
6	0.13		0.02	1.00

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