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Using the five sectors sustainability model to verify the relationship between circularity and sustainability

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ABSTRACT

It is known that the current linear socioeconomic system, characterized by "production-use-destination," is unsustainable and the leading cause of the depletion of natural resources. In the search for sustainable development, several actions to preserve resources in use for as long as possible have been proposed in recent decades, such as cleaner production, ecoefficiency, industrial ecology, industrial ecosystems, industrial symbiosis, and the circular economy. Although circularity and sustainability are increasingly present on the agenda of academics, entrepreneurs, and government sectors, the relationship between the two concepts is still under construction. In this sense, this work aims to verify, using the Five Sectors Model of Sustainability, the relationship between circularity and sustainable development in ASEAN, Mercosur, and the EU, considering economic, social, and environmental indicators in the periods between 2000 and 2020. The selected indicators with their respective goals were applied and weighted through Goal Programming. From the primary and secondary data analysis, it was not possible to conclude that circularity alone guarantees sustainability, despite contributing significantly to sustainable development. However, the results obtained in the 5SEnSU model made it possible to verify that the EU has a superior performance for sustainable development of the other two blocks and that the impacts generated in the economic system (sector 3) of the analyzed blocks benefited social sectors (4 and 5) to the detriment of environmental integrity (sectors 1 and 2). Some challenges still need to be mitigated, such as those related to excessive consumption and waste discharge, so that a circular economy can effectively contribute to global sustainability.

1. Introduction

The linear socioeconomic system, characterized by the disposal of the product at the end of its useful life, is causing the depletion of natural resources. Zhao et al. (2019) claimed that the linear economic model of "production-use-disposal" is unsustainable since products after use are discarded as waste. Manufacturing new products requires more materials to be taken from the environment. Geerken et al. (2019) reported that in pursuing sustainable development, several actions focused on industrial symbiosis, cleaner production, and, more recently, the Circular Economy (CE), which brought conceptual, technological and/or managerial advances toward a sustainable society (Giannetti et al., 2020).

CE is an evolving concept that encourages reducing the dependence on finite and non-renewable resources, emphasizing "the need for the economic activity of consumption to eliminate waste from the system in principle" (Ellen Macarthur Foundation, 2012). Economies such as Germany in 1996 and China in 2010 developed CE-related policies (Lieder and Rashid, 2016). In 2015 the European Commission drew up an action plan to accelerate Europe's transition to a circular model. Later, different regions sought to promote CE to achieve sustainable development based on decoupling the consumption of finite resources from economic activities. However, comprehensive macro-scale assessments are rare (Avdiushchenko and Zajac, 2019).

Although CE has become an increasingly solid concept (Ghisellini et al., 2016), the literature review pointed out that few studies still focus on circularity measurement for regions. Analyzing CE indicators at the macro level can provide a valuable guide to see which areas need to step up their efforts for this transition (Avdiushchenko and Zajac, 2019). For Mayer et al. (2019), establishing monitoring indicators at the macro level would allow capturing the effects of the entire system, including the "rebound effects." These monitoring indicators would be beneficial

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to supporting the policies that focus on reducing environmental impacts triggered by the use of resources.

As reported, the CE has potential benefits on a global scale concerning environmental, economic, and social capital. CE promotion aims to contribute to sustainable development in the same way that it can drive progress towards the achievement of the Sustainable Development Goals – SDGs (Schroeder et al., 2019), especially in what concern conservation, poverty, inequality, and gender equality (Dantas et al., 2021). For Cecchin et al. (2021), some CE-related issues have not yet been widely explored, and trade-offs related to scale impacts (spatial and temporal) must be analyzed from different national and regional perspectives.

In this context, considering the conflicting relationships on a global scale between developed and developing economies in the broader field of Sustainable Development and intending to verify whether the ambitious goals established by the European Parliament in 2015 directly helped the European Union (EU) or indirectly ASEAN and Mercosur for a transition to CE, this research aims to verify, through the application of the Five Sectors of Sustainability Model (5SEnSU), what is the relationship between circularity and sustainability in ASEAN, Mercosur and the European Union.

The 5SEnSU Model has been successfully applied to analyze sustainability at various levels, from the case of Mercosur countries (Giannetti et al., 2019); comparing production systems across countries (Moreno et al., 2021), and measuring inequality in terms of resource use in the case of Mozambique (Langa, 2019). At the meso level, the 5SEnSU Model was employed by Cha (2020) to deal with the geographical indication (GI) of production systems. Finally, at the micro-level, the 5SEnSU Model was used by Agostinho et al. (2019) to assess transport modes for the soybean produced in Brazil.

Given the above, the present research paid particular attention to CE indicators at the macro level due to the need to monitor the transition to circular systems and measure its effects in regions under environmental, economic, and social aspects. Special attention was also given to the fact that most theoretical and practical works that address the CE theme focus on the China-European Union axis; therefore, knowing the circular dynamics in other geographic axes is potentially contributory both academically and managerially.

Another aspect studied is that most existing indicators are one-dimensional and analyze single aspects of CE (Cavaleiro de Ferreira and Fuso-Nerini, 2019), primarily related to the preservation of materials (Moraga et al., 2019), which makes it difficult to measure the "circularity" of products, companies or regions (Rincón-Moreno et al., 2021). Many of these indicators leave the social dimension uncovered, which has been questioned for not representing the systemic nature of sustainability (Banaité, 2016) which can have unintended consequences for ecosystem functioning and human well-being (Murray et al., 2017). To fill this gap, CE progress in this work was measured by ten indicators covering economic, social, and environmental aspects combined into a single index guided by the 5SEnSU Model (Giannetti et al., 2019), which provides a valuable tool both for understanding and monitor the possible contribution of CE to sustainable development in all its dimensions.

The main objectives of the work are to use indicators commonly used to measure circularity combined with socioeconomic indicators to evaluate progress towards sustainability. Indicators are organized using the Five Sectors Sustainability Model, placing society as the system's beneficiary and setting the economic bloc trends in a time series that may help draw public policies to prioritize future actions.

2. Literature review

The Stockholm Conference in 1972 and the Brundtland Report in 1987 raised concerns about unsustainable development, uncontrolled growth, and the risks to future generations of not meeting their own needs (Somogyi, 2016). Linked to these concerns, movements have emerged focusing on the multifaceted interactions between nature, economy, and society, pinpointing that environment and development must walk together (Troullaki, 2021).

Within this broad scenario, intense debates with different environmental ideologies endeavored to combine the concepts of development and sustainability and intense discussions to position circularity within the general discussion on sustainable development. Regarding sustainable development, despite the emerging challenges, sustainability is seen from a multidimensional perspective that integrates, in a balanced and systemic way, economic, social, and environmental performances (Scoones, 2007). For Schoolman et al. (2012), research on sustainability should incorporate knowledge from various academic disciplines that permeate the social, economic, and environmental sciences as there is an inevitably experimental nature to sustainability that sometimes does not reflect social needs (Kajikawa et al., 2014). For Geissdoerfer et al. (2017), despite theoretical and conceptual divergences, there is a need to transition to more sustainable systems. Both concepts of sustainability and sustainable development make room for multiple expectations. According to Sauvé et al. (2016), CE and sustainable development are complementary approaches since the first concept establishes several intergenerational objectives. The second brings tools that can be used for sustainable purposes.

CE has been considered an essential strategy to improve the overall performance towards sustainability as its principles aim to benefit the environment, economy, and society in general. Kirchherr et al. (2017) reviewed the literature and analyzed 114 definitions, identifying different principles such as reuse, recover, reduce and recycle to understand the ambiguities in the CE definitions. In similar work, Homrich et al., (2018) also found a lack of consensus on terminology and definitions in the literature, which is why research on CE is currently fragmented.

Kirchherr et al. (2017) showed a growing need for a clear and objective conceptualization of standard approaches to CE to define boundaries and interfaces concerning other concepts and models since switching from a linear to a circular model is not a simple task (Van Loon and Van Wassenhove, 2020). The Ellen MacArthur Foundation (Ellen Macarthur Foundation, 2012) conceptualized CE as the economic activity that contributes to the planet's well-being by reducing the negative impacts of the linear economy. Prieto-Sandoval et al. (2018) considered CE as the expression of a paradigm shift requiring changes in how society innovates, produces, consumes, and legislates to respond to environmental and social needs. For Korhonen et al. (2018), CE limits production flow to a level tolerated by nature and mimics ecosystem cycles in economic cycles according to the natural production rate. Sauvé et al. (2016) advocate that CE considers the impact on the environment of waste and resource consumption, creating a model where resources circulate within the production and consumption levels.

In the search for sustainability, the idea of CE is not new. It comes from several schools of thought that contributed to conceptualizing the balanced integration of economic activity and environmental well-being in a sustainable way (Murray et al., 2017). Andersen (2007) cited that the principles of environmental economics and ecological economics aggregated several concepts to develop a structural model for the CE system, highlighting the efficient use of resources according to the market practices and the interdependence of the economy and natural ecosystems across space.

In the academic debate on the shift from the current linear model of the economy to a circular model that can generate enormous financial, social, and environmental benefits (Lewandowski, 2016) described the essential contributions of industrial ecology in the relationship between industry and the environment in the quest to keep the resources used by industry within the production cycle. Over the last 50–60 years, other disciplines such as industrial symbiosis, regenerative design, industrial metabolism, the cradle-to-cradle approach, biomimicry, the blue economy, permaculture, and natural capitalism provided the basic principles of CE (Haas et al., 2020). It is undeniable that these previous ideas prepared the ground for the CE; however, the significant differential of the concept is the idea of circularity, including the consumer as an interested party in the discussion for the mitigation of environmental impacts.

Despite the different narratives found in the literature, some researchers have criticized a deficiency of social aspects in CE concepts, tools, and metrics, which would only prioritize the economy bringing benefits to the environmental system (Mies and Gold, 2021). Padilla-Rivera et al. (2020) highlighted that non-profit activity and other social issues related to working conditions and distribution of resources wealth are often not addressed in CE studies. Likewise, Moreau et al. (2017) reported the absence of a holistic framework for the social indicators selection to assess the positive or negative impacts of circular initiatives. Consequently, CE is not seen as a tool to promote/encourage social equity.

While there is a frequent association between CE and sustainability, CE has yet to demonstrate that they contribute to achieving some SDGs (Walker et al., 2021). In this context, several conceptual approaches that directly debate the interface between environment, development, and society began to emerge to ensure that the purpose of the 2030 Agenda is achieved with the help of CE practices (Belmonte-Ureña, 2021). Rodriguez-Anton et al. (2019) analyzed the interrelationships between the CE model and some characteristics of sustainable development. They concluded that, despite the limitations, CE is one of the most promising means to guide the transitions to accomplish at least some SDGs. Even though the term CE in the SDG targets is not clear, several studies link both concepts and show that circularity practices can directly lead to achieving a significant number of SDGs (Dantas et al., 2021).

2.1. Overview of CE indicators

As CE is a concept under construction, there is still no common standard to verify its progress toward sustainability (Kristensen and Mosgaard, 2020). Therefore different assessment tools and analytical techniques can be used to facilitate its understanding. Furthermore, the subjective methodological framework currently in place to assess and analyze the effects of CE adoption at different systemic levels has potentially harmful implications for advancing sustainability (Saidani et al., 2019).

With this, several studies are being proposed and discussed to evaluate, improve, monitor, and communicate the performance of the CE, covering different purposes, scopes, and potential uses. After reviewing 16 CE indicators covering 14 environmental assessment methodologies, Elia et al. (2017) claimed that an effective measurement process must consider four levels: processes to be monitored, actions involved, requirements to be measured, and, finally, the levels of implementation. Kristensen and Mosgaard (2020) reviewed the literature and found 30 indicators for EC at the micro-level, which were classified into three categories: (1) single quantitative indicators presenting circularity as a single number, (2) analytical guidelines, tools, and models, and (3) composite indicators merging a and b.

More practically, Saidani et al. (2019) named the circularity indicators C-Indicators and identified 55 sets developed by academics, consulting firms, and government agencies. Eco-design tools and sustainability indicators inspired these C-Indicators.

Exploring this theme, Parchomenko et al. (2019) focused efforts to understand the current framework of CE metrics and perspectives and used the Multiple Correspondence Analysis (MCA) method. After studying 63 circularity metrics, they identified 24 elements that allowed the recognition of three main groups of metrics frequently evaluated (resource efficiency, inventories and material flows, and product-centric). Kravchenko et al. (2019) reviewed key performance indicators related to sustainability and found more than 270 performance indicators, classifying them according to three categories: dimensions of sustainability, business processes, and EC strategies. For these authors, these three categories of performance indicators make it possible to measure the potential sustainability performance of circular designs before their implementation.

Regardless of the level (nano, micro, meso, or macro), Figge et al. (2018) postulated that most EC indicators fail to simultaneously consider circularity and time resource is in use and suggested a longevity indicator. Time calculations are essential in CE because they allow measuring the circularity of a given material based on the amount of time a resource used in the composition of a product is kept in use (Franklin-Johnson et al., 2016). Rodriguez-Anton et al. (2019) argued that CE adoption is a challenge at both micro, meso, and macro levels, and the voluntary adoption of circularity practices is still a barrier to be overcome. Therefore, it is significant to have strong regulations and policies for the CE adoption, and institutional pressure plays a predominant role in this context.

If, on the one hand, the excess of CE indicators may not bring the desired positive effects, especially in the broader context of sustainability, the lack of quantitative and qualitative metrics or poorly understood indicators can result in superficial circularity assessments. Given this, Rincón-Moreno et al. (2021) advocated that indicators to measure different levels of CE should be a high priority for stakeholders to track progress on circular initiatives.

2.2. CE indicators for regions

Due to the complexity present in regions, several indicators proposed in the literature do not cover all the critical variables associated with an EC (Linder et al., 2017), and this implies the need for a set of multidimensional indicators instead of a single one (Cayzer et al., 2017). Given this context, several studies have proposed CE indicators, and some studies have shown that existing tools for monitoring are inadequate to track the progress of the transition to circularity at the regional level (Avdiushchenko and Zajac, 2019).

Tantau et al. (2018) pointed out that there are almost no regional-specific indicators dedicated to circularity, and the existing ones are inadequate to track the progress of the EC transition at the regional level, which makes it difficult to compare the effects of EC implementation across regions (Silvestri et al., 2020). Therefore, Garcia-Bernabeu et al. (2020) recommended that it is necessary to develop a composite CE indicator to compare the performance of countries at the national level on a single summary indicator. As a result, several circularity indicators have been developed recently, and several index-based methodologies have been proposed to measure CE performance in countries and regions.

Kalmykova et al. (2018) reviewed the literature on the subject. They found that the most addressed aspects of achieving EC were stock optimization, eco-efficiency and eco-effectiveness, waste reduction, and the 4Rs and, from there, developed two tools - EC Strategies Database and CE Implementation Database - to facilitate CE design. At the national level, in China, indicators include material recycling, waste generation, and energy and water use, among other metrics to monitor the transition to a CE (Geng et al., 2013).

For Triantaphyllou (2000) TOPSIS should be widely used in frameworks due to its ease of implementation and ability to consider an unlimited number of alternatives and criteria. Khan et al. (2021) applied the ReSOLVE framework (ReGenerate, Share, Optimize, Loop, Virtualise, Exchange) to examine the role of blockchain technology in circular practices and its impact on eco-environmental performance, using data from 404 companies located in Chinese and Pakistani territories. Mhatre et al. (2021) also applied the ReSOLVE framework to understand the implementation of circular practices in all European Union member states. Still, in the European context, Sánchez-Ortiz et al. (2020) used Data Envelopment Analysis (DEA) to measure the efficiency of EC processes and products in countries of the bloc, and Mazur-Wierzbicka (2021) created the Circular Economy Development Index (IDCE) to track and compare changes in spatial differentiation as countries advance in CE implementation over the years.

Ngan et al. (2019) proposed an indicator model for developing countries, adopting the Fuzzy Analytical Network Process to quantify the priority of sustainability indicator weights for a transition to EC. However, Busu and Trica (2019) warned that even when indicators are developed to monitor and evaluate regions, it is necessary to consider the economic situation of each country.

Up to this point, a wide range of studies has provided analytical discussions of EC implementation strategies at the macro level and proposed systems of calculated indicators for countries and regions. However, the many studies are one-dimensional and analyze only one aspect of CE (Cavaleiro de Ferreira and Fuso-Nerini, 2019), often leaving the social dimension uncovered, which has been questioned for not representing the systemic nature of sustainability (Murray et al., 2017). To fill this gap, the present study analyzed CE progress in ASEAN, Mercosur, and the European Union from 2000 to 2020, covering environmental, economic, and social aspects, combined into a single index using the 5SEnSU Model.

The methodological framework used in 5SEnSU provides a holistic and simplified approach that simultaneously accounts for environmental (sectors 1 and 2), economic (sector 3), and social (sectors 4 and 5) dimensions. The model allows appraising the CE contribution to the sustainability of selected economic blocks because decision-making within the scope of sustainable development should not be exempt from social responsibility (Suárez-Eiroa et al., 2019). The use of the 5SEnSU Model alleviates the limitations of establishing a set of common indicators to measure circularity as it encompasses the various dimensions indicated by the European Commission (2018), that is, (i) production and consumption, (ii) waste management, (iii) secondary raw materials and (iv) competitiveness and innovation. In addition, the 5SEnSU Model can be used in various geographic areas due to its replicability and adaptation to each case since the food data are standard indicators that apply to all countries, allowing comparisons between them.

3. Materials and methods

As the main objective of this study is to verify the relationship between circularity and sustainability in different regions, the choice of ASEAN, Mercosur, and the EU allows us to contrast three economic blocks with different levels of circularity and varied sustainability strategies. In addition to the differentiated nature, the regions have policies, legislation, and instruments that lead to an understanding of sustainability and circularity and make it possible to build an analysis framework capable of comparing the three blocks.

The EU was chosen as the most progressive bloc in terms of policy measures designed for the transition to the CE (Kirchherr et al., 2018), actively promoting the concept since 2015 with a monitoring framework to measure progress and assess the effectiveness of circular initiatives in the bloc and its Member States (Garcia-Bernabeu et al., 2020). Subsequently, the other two economic blocs - ASEAN and Mercosur – were chosen to consider some similarities between the two blocks (developing countries, emerging economies, huge consumer markets) and dissimilarities with the EU – mainly composed of developed countries and stable economies.

As it has a robust and comprehensive scientific structure that identifies supply and demand factors in production systems' social, environmental, and economic dimensions, the 5SEnSU Model provides assertive parameters for decision-making concerning sustainability. The 5SEnSU Model considers the environment as a supplier and receiver, with sector 1 having the function of origin in the supply of natural resources and sector 2 the function of receiving waste generated by sector 3 (Fig. 1). Sector 3 is the production and consumption unit or the system of interest. Sector 4 is the provider of socioeconomic resources, and sector 5 represents society as the receiver of resources generated by Sector 3 (Giannetti et al., 2019).

With the support of the literature, it was possible to define the

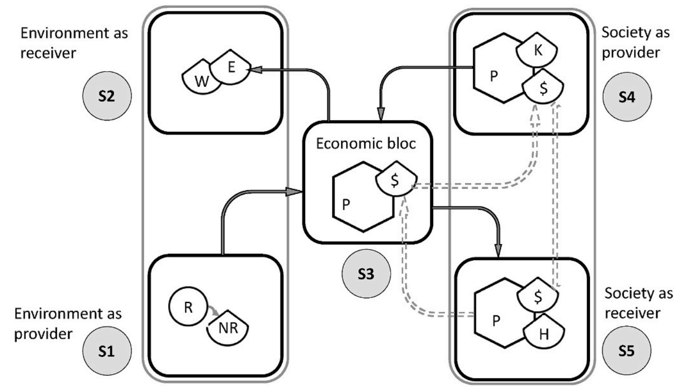

Fig. 1. Schematic representation of the 5SEnSU Model. Where W: waste; E: emissions; R and NR: renewable and non-renewable resources; P: people; K: knowledge and H: happiness. Straight lines refer to material and energy flows and dashed lines to currency flows.

indicators to be considered in the 5SEnSU Model according to the indicators used by the different CE approaches. These indicators and indices seek to link the concept of CE to sustainable development in all three dimensions (environment, society, and economy), as suggested by Kirchherr et al. (2017). Economic, social, and environmental data were collected from international organizations in the time interval between 2000 and 2020, with annual observations. These 20 years cover the introduction of CE policies globally, especially in the EU in 2015, and allow verifying the possible advances along the period. It must be emphasized that even using few indicators to build the SSIS; they were carefully selected based on the scientific literature and encompass the various dimensions indicated in the monitoring structure of the EC of the European Commission (2018), that is: (i) production and consumption, (ii) waste management, (iii) secondary raw materials and (iv) competitiveness and innovation.

To represent the donor and recipient functions of the natural environment and society and seek a balance in terms of the number of indicators, two indicators were chosen for each sector of the 5SEnSU Model (Table 1).

CE is examined under multiple aspects using the 5SEnSU Model (Table 1), and as sustainability assessments require a set of multidimensional indicators (Munda, 2005) that presents a scientifically sound and operationally implementable conceptual framework (Diaz-Balteiro et al., 2020), the use of Multi-Criteria Decision Making techniques helps to determine the sustainability of the systems of interest (Garcia--Bernabeu et al., 2020). In this case, the Goal Programming philosophy developed by Charles et al. (1955) and improved by Charles and Cooper (1957) is used as a tool to obtain a Synthetic Indicator of Sustainability of the System (Moreno et al., 2021).

The two indicators selected per sector are represented by the letter "K" followed by two numbers; the first indicates the sector, and the second refers to the selected indicator. The value of each indicator is set to be maximized or minimized according to pre-established goals for each one (Table 2). These indicators were selected so that the different sustainability dimensions (social, environmental, and economic) are included in analysis and comparisons, allowing the assessment of the effects and benefits of the proposed CE initiatives.

Subsequently, the selected indicators with their respective targets are applied in the multi-criteria linear goal programming (for details see Giannetti et al., 2019), which allows comparisons among the economic blocs. Table 2 shows the 10 indicators used for the five sectors, the objectives (maximize or minimize), the SDGs to be achieved with their respective justifications, and the goals established for each indicator.

Although all data collected for CE indicators are available from open data sources, a potential difficulty of the project was how to update some outdated data. Due to some years' lack of statistical data, estimates were

Table 1
Indicators, units, and source databases used in each sector.

Sector	Function	Indicator	Unit	source
1	Environment as material/energy provider	Emergy	sej/person year	http://www.emergy-nead.com
		Renewable energy consumption	% of total energy consumed	https://data.worldbank.org
2	Environment as waste receiver	CO2 emission	ton per capta/year	https://data.worldbank.org
		Electronic Waste	kg per capta/year	https://unstats.un.org
3	Economic blocs	GDP	US$ per capta/year	https://data.worldbank.org
		GINI	Annual index	https://data.worldbank.org
4	Society as resource provider	Economic openness index*	Annual index	a.https://data.worldbank.org b.https://www.trademap.org
		Employment rate	Annual index	https://data.worldbank.org
5	Society receiving products	Human Development Index	Annual index	https://data.worldbank.org
		Gross Happiness Index	Annual index	https://worlddatabaseofhappiness

* To assess circularity more accurately, bilateral trade between countries within blocs was considered for the calculation of the Economic Openness Index. Thus, "a" was used for exports, imports, and Gross Domestic Product (GDP) of the country and "b" for bilateral exports and imports between countries of the same economic bloc.

made for some periods based on the available values using a scatter plot with a trend line in the Microsoft Excel ® program (Supplementary Materials, Table S01, and S02).

The Goal Programming was applied for the multicriteria modeling to show the deviations from the goals that affect the values of the selected indicators. The main steps of the 5SEnSU modeling proposed by Giannetti et al. (2019) are briefly presented, and for more details please consult Giannetti et al. (2019) and Moreno et al. (2021). The Index of Sustainability Goal, ISG (Eqs. (1) and (2)) indicates how far the indicator is from its goal, considering the weight/punishment chosen for analysis (Agostinho et al., 2019). The sum of the differences between the positive (+) and negative (−) deviations makes it possible to generate the Sector Sustainability Indicator (SSI, Eq. (3)). After this step, adding the SSIs, it is possible to calculate the Sustainability Synthetic Indicator of System (SSIS) that represents the five sectors together (Eq. (4)). The SSIS represents the sustainability performance of the system as a whole, considering the relationship between the indicators (Agostinho et al., 2019) as the shortest distance to the established target. Therefore, the lower the SSIS, the greater the system's sustainability (Giannetti et al., 2019). The detailed calculations and a step-by-step procedure are provided in the Supplementary materials (The 5SEnSU model and the use of goal programming to calculate the Synthetic Indicator of Systems Sustainability - SISS).

$$ISG^{+}_{ijk} = \sum_{ijk} \frac{N^{+}_{ijk}}{W^{+}_{jk}.G^{+}_{jk}} + \sum_{ijk} \frac{P^{+}_{ijk}}{W^{+}_{jk}.G^{+}_{jk}} \forall i \in \{1,2,\ldots,NE\} \forall j \in \{1,2,\ldots,NS\} \forall k \in \{1,2,\ldots,NI\} \quad (1)$$

$$ISG^{-}_{ijk} = \sum_{ijk} \frac{N^{-}_{ijk}}{W^{-}_{jk}.G^{-}_{jk}} + \sum_{ijk} \frac{P^{-}_{ijk}}{W^{+}_{jk}.G^{-}_{jk}} \forall i \in \{1,2,\ldots,NE\} \forall j \in \{1,2,\ldots,NS\} \forall k \in \{1,2,\ldots,NI\} \quad (2)$$

Table 2
Indicators and relative targets proposed to feed the 5SEnSU model in the evaluation of economic blocks, where MIN is minimize and MAX maximize.

Sector	Indicator	Objective	SDG/justification	Goal
1	K11: Emergy per capta	MIN	SDG 15 Minimize the environmental impact caused by the exploitation of renewable and non-renewable resources (Liu et al., 2014, Viglia et al., 2018)	$\overline{K_{11}} + \sigma(K_{11})$
	K12: Renewable energy consumption	MAX	SDG 15, SDG 7 Indicator 7.3. By 2030, double the global rate of energy efficiency	$\overline{K_{12}}*2$
2	K21: CO2 emission	MAX	SDG 9, SDG 13 Reduce emissions by 7.6% each year from 2020 to 2030 (UNEP Emissions Gap Report, 2020)	$\overline{K_{21}} -$ 54.64%
	K22: Electronic Waste	MIN	SDG 9, SDG 11 e SDG 12.	$\overline{K_{22}} + \sigma(K_{22})$
3	K31; GDP	MAX	SDG 8 2019 global average PPP GDP per capita	21,932.67
	K32: GINI	MIN	SDG 1, SDG 10 Lowest global average value between 2000 and 2019	0.395
4	K41: Economic openness index	MAX	SDG 10 The current international situation increasingly encourages the interdependence of resources between countries (Geerken et al., 2019)	$\overline{K_{41}} + \sigma(K_{41})$
	K42: Employment rate	MAX	SDG 8 Highest global average value of the employment rate between 2000 and 2019	62.54
5	K51: Human development Index	MAX	SDG 1; SDG 3; SDG 4 and SDG 10 HDI = 0.8 as highest value	0.80
	K52: Gross Happiness Index	MAX	SDG 3 and SDG 16 the 10 happiest countries have values above 7.0	7.0

$$SSI_{ij} = WS\sum_{ijk}\left(ISG^{+}_{ijk} - ISG^{-}_{ijk}\right)\{1,2,\ldots,NE\}\forall j \in \{1,2,\ldots,NS\}\forall k \in \{1,2,\ldots,NI\} \quad (3)$$

$$SSIS_{i} = \sum_{j}^{5} SSIS_{i}\{1,2,\ldots,NE\}\forall j \in \{1,2,\ldots,NS\}\forall k \in \{1,2,\ldots,NI\} \quad (4)$$

Where:

N_ijkˆ+ and N_ijkˆ- = positive and negative indicators for the negative deviation variables;
P_ijkˆ+ and P_ijkˆ- = positive and negative indicators for positive deviation variables;
G_jkˆ+ and G_jkˆ- = Goals (Goals for positive or negative indicators);
W_jkˆ+ and W_jkˆ- = Weight (weight of each indicator);
NE = number of systems (economic blocks)
NS = number of sectors (1 … 5)
NI: number of indicators per sector
i: evaluated system (1 … NE)
j: sectors for the 5SEnSU Model (1 … 5)

k: indicators for each sector evaluated (1 … NI)

WS (Weight Sector, Eq. (3)) is the weight established for each sector (in this case, equals one), considering that the 5SEnSU Model seeks the balance between the five sectors (Gianetti et al., 2019; Agostinho et al., 2019).

4. Results and discussion

The performance of the analyzed economic blocks translated by the Synthetic Indicator of Systems Sustainability - SISS in the 5SEnSU Model is presented in Fig. 2. Lower values of this indicator correspond to higher sustainability since the general performance is closer to the established goals (Giannetti et al., 2019). Table 3 shows the indicators for each sector, allowing to identify each economic bloc's strengths and weaknesses.

Results in Fig. 2 show that the EU has the lowest SISS values since 2011, mainly due to the political and environmental actions adopted by the bloc. As reported by Mazur-Wierzbicka (2021), some EU countries have already adopted strategic packages that support the CE principles. However, most of the strategies and plans of each country do not measurably specify their objectives. In 2000, the region occupied an intermediate position according to the 5SEnSU's synthetic indicator, with 11.609 for the EU bloc, 9299 for ASEAN (24.84% lower), and 13, 865 for Mercosur (49.10% higher). EU's performance in 2000 was better regarding sectors 1 (environment as provider), 4 (society as provider), and 5 (society as receiver), see Table 3. However, the intermediate position of the EU was defined by its relationship with sector 2 (environment as receiver) since the indicators for sector 5 were comparable to those of the other blocs. In 2020, the EU block presented the lowest indicators in sectors 1, 2, and 5, indicating that improvements are needed in its relationship with sector 4. Considering all indicators together, the $SISS_{2020} = 9205$ was 68% lower than the ASEAN's ($SISS_{2020} = 15{,}514$), and 104% lower than Mercosur's ($SISS_{2020} = 18{,}774$). In his research, Busu and Trica (2019), using econometric model, revealed that the environmental factors of CE were significant in economic growth in all 27 EU countries, which proves that the results found in the 5SEnSU Model are in agreement with recent work on the impact of EC in economic development, such as the research by Biber--Freudenberger et al. (2018) for example, who highlighted that sustainability is not improved by a simple switch to renewable resources or materials.

An important aspect to consider is that even with the EU presenting the lowest SISS in 2020, when the temporal analysis from 2000 to 2020 is examined, the lowest SISS values till 2005 refer to ASEAN (Fig. 2; Table 3). Although with better indicators till 2005 from a general perspective in sector 2, ASEAN presented higher indicators in sector 3 (GINI, GDP). It occupied the 9th position, indicative of high inequality and low income *per capta*. In sector 4 (society as a labor and technology supplier), ASEAN occupied the 7th position. In sector 5 (society as a receiver of goods and services), ASEAN occupied the 13th position, revealing a performance deterioration in relation to 2000 when it occupied the 3rd SISS position – with the first position in sectors 1 and 4, and the second position in sector 2, although positions in sectors 3 and 5 were 10th and 15th, respectively. This pattern discloses how the economic development (sector 3) resulted in environmental consequences in sectors 1 and 2.

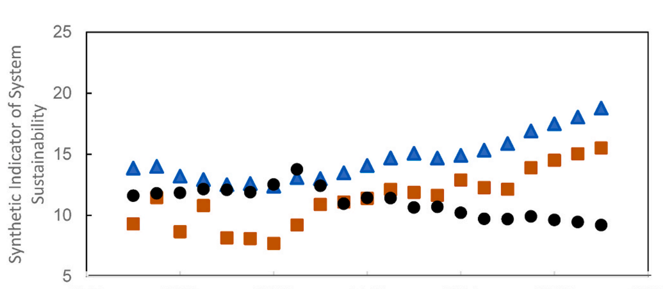

Fig. 2. Synthetic Indicator of Systems Sustainability - SISS for ASEAN (■), Mercosur (▲), and the European Union (●) in the period from 2000 to 2020. Lower values indicate higher sustainability. The detailed temporal analysis from 2000 to 2020, examined at 5-year intervals, is shown in Table 3.

Mercosur presented the worst sustainability index when all indicators are considered in the analyzed period, evidenced by the SISS of 18,774 in 2020. It is interesting to note that Mercosur, even occupying the last positions in the sustainability ranking, has good results in the environmental aspect. In 2000, even occupying 11th overall position, the block was in fourth place in sectors 1 and 2. Similarly, in 2005 it occupied the 10th position in the SISS and in sectors 1 and 2 it occupied the fifth and third positions, respectively.

The EU in 2020 presents the 2nd best performance in the sustainability ranking when all indicators are considered for all years; however, sector 4 in the 14th position pulled down the position in the overall analysis. The conclusion of the work by Grafström and Aasma (2021) warns that even small barriers can prevent an EC from proliferating to the macro level, that is, not encouraging consumption reduction, behavioral change, and improving production efficiency, among other aspects, can directly influence the circular strategies, several results in social, economic and environmental indicators due to the complexity present in each region (Bassi et al., 2021). Thus, there is a need for specific public policies for improving indicators K41 (Economic openness index) and K42 (Employment Rate). Still, even with deficiencies in sector 4 (society as a supplier), sector 5 (society as the recipient) shows a good performance for the bloc, which stands in the first position. In addition to sector 5, in 2020, the European bloc obtained good results in sector 1 (2nd place) and sectors 2 and 3. Aguilar-Hernandez et al. (2021) carried out a meta-analysis of CE scenarios in the EU from 2020 to 2050 and found that GDP and job creation variations showed incremental variations, which partly explains the results obtained by the bloc in this period. A similar situation is found in 2015 and 2010, where the bloc performed well in sectors 1, 2, 3, and 5.

The general discussion resulting from the data analysis provides several findings that can be seen in Fig. 3, which shows an overview of the trends of the economic blocs' performance in each sector. Analyzing these results in detail, it is possible to clearly verify differences concerning the changes over two decades in the three blocks studied. Mazur-Wierzbicka (2021), using statistical methods, reported that many studies had evaluated ways of measuring progress towards CE at various levels, despite little understanding of the magnitude of a transition's potential socio-economic and environmental impacts to a fully circular integrated model at the macro-level (Aguilar-Hernandez et al., 2021). Therefore, identifying which policy measures can be implemented to promote a transition to circularity (Geng et al., 2012) will be effective when the circularity radius reaches a sufficiently large size to affect a considerable part of the economy (Alaerts et al., 2019).). It is not only possible to follow the relationship of the blocs with each sector but also to depict the contribution of each sector to the overall sustainability since the overall SISS values reflect how close the sum of the obtained sector indicators are to the established goals (Giannetti et al., 2019). Clearly, the relationship with sectors 1 and 2 should be improved in all blocs, and indicators related to sectors 4 and 5 contribute little to the SISS value, even though there are significant differences among the blocs (see details in Fig. 4). This result may have two interpretations. The first leads us to think that the goals established for the indicators of sectors 4 and 5 are still mild and that more ambitious goals could be considered. The second is permeated with the idea that, if the established goals are adequate, then most efforts should be directed to solving the problems connected to the relationship of the blocks with the environment, especially with sector 2. Upon the multi-criteria analysis, the EU decreased the SISS in all isolated sectors thanks to actions carried out at national and regional levels. Since 2014, approximately 16

Table 3
Sustainability ranking for ASEAN, Mercosur, and the European Union considering periods of 5 years. Green arrows correspond to improvement, while red arrows highlight performance descent.

			Sector				
Ranking	SSIS	Year	1	2	3	4	5
			EU				
7º	11.609	2000	3.222	6.692	0.254	0.422	1.019
8º	11.894	2005	3.170	7.415	0.004	0.420	0.885
6º	11.429	2010	↓ 2.588	↔ 7.718	↓ 0.007	↔ 0.381	↓ 0.735
4º	9.714	2015	2.570	6.182	0.010	0.354	0.598
2º	9.205	2020	2.109	6.257	0.014	0.489	0.336
			ASEAN				
3º	9.299	2000	2.065	4.271	1.706	0.001	1.255
1º	8.096	2005	2.255	3.684	1.013	0.139	1.004
5º	11.393	2010	↑ 2.506	↑ 7.927	↓ 0.142	↔ 0.002	↓ 0.816
9º	12.269	2015	2.781	8.857	0.001	0.002	0.629
14º	15.514	2020	2.893	12.109	0.002	0.002	0.509
			MERCOSUR				
11º	13.865	2000	2.353	5.020	4.981	0.631	0.88
10º	12.598	2005	2.411	4.807	4.364	0.146	0.868
12º	14.076	2010	↑ 2.765	↑ 7.219	↓ 3.267	↓ 0.003	↔ 0.822
13º	15.333	2015	3.446	8.686	2.456	0.003	0.742
15º	18.774	2020	4.527	11.112	1.939	0.246	0.950

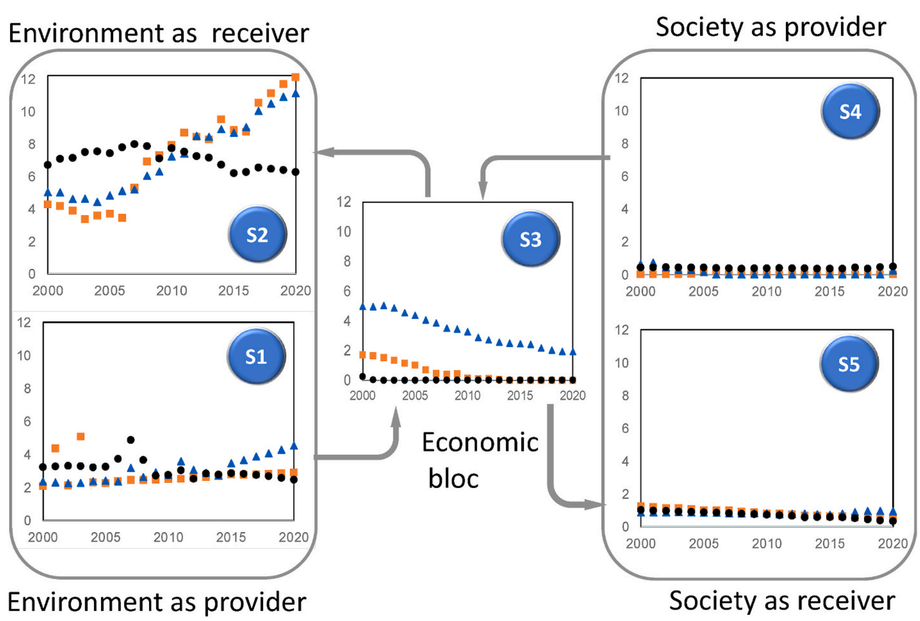

Fig. 3. Results of the 5SEnSU Model for the five sectors from 2000 to 2020. Lower SISS values correspond to greater proximity to the pre-defined goal and, therefore, higher sustainability. The years analyzed are on the X-axis, the SISS value on the Y-axis, and ASEAN is represented by (■), Mercosur (▲), and the European Union (●).

countries have developed national and regional strategies to implement CE systems (Johansson and Henriksson, 2020) to mobilize the transformation to an EC (Smol et al., 2021).

The results shown in Fig. 3 evidence that all blocs are reducing the distance between performance indicators and the established goals in sector 3, but ASEAN and Mercosur still pursue these goals to the detriment of the environment, especially in sector 2, where CO_2 emissions and electronic waste are considered (Fig. 4).

Regarding sector 1 (K11 - Emergy *per capta* and K12 - Renewable energy consumption), as the shortage of natural resources is the main factor that affects the efficiency and stability of the economy and production, a sustainable CE should be based on the rational use of resources (Trica et al., 2019). In such conditions, reducing or even eliminating the consumption of natural resources requires enormous challenges to balance economic development and environmental protection adequately. Fig. 4 shows that the EU is gradually progressing towards the established goals for sector 1, while the inverse is observed for Mercosur and, more markedly, for ASEAN. One explanation could be that significant progress was made in favoring economic benefits or even environmental gains that generate these benefits since the transformation processes carried out in sector 3 are highly dependent on the environmental basis. While these results may offer a positive view on the degree of CE implementation and that circularity has the potential to reduce social and ecological burdens (Korhonen et al., 2018), the indicators for sector 2 (K21 – CO_2 emission and K22 – Electronic waste) are still far from the pursued goals, and this can affect the total capacity of the system for sustainable development.

The ASEAN, Mercosur, and the EU face an urgent challenge in reducing electronic waste generation, as consumers replace their products with others launched on the market due to technological advances. About this situation, Horvath et al. (2019) questioned whether world economies (represented here by economic blocks) are on the right track to minimizing resource and energy use through CE practices or perhaps just increasing the demand for products because process efficiency has allowed the increased consumption of goods and services (Oliveira et al., 2021). Thus, instead of achieving the desired effect in some cases, more

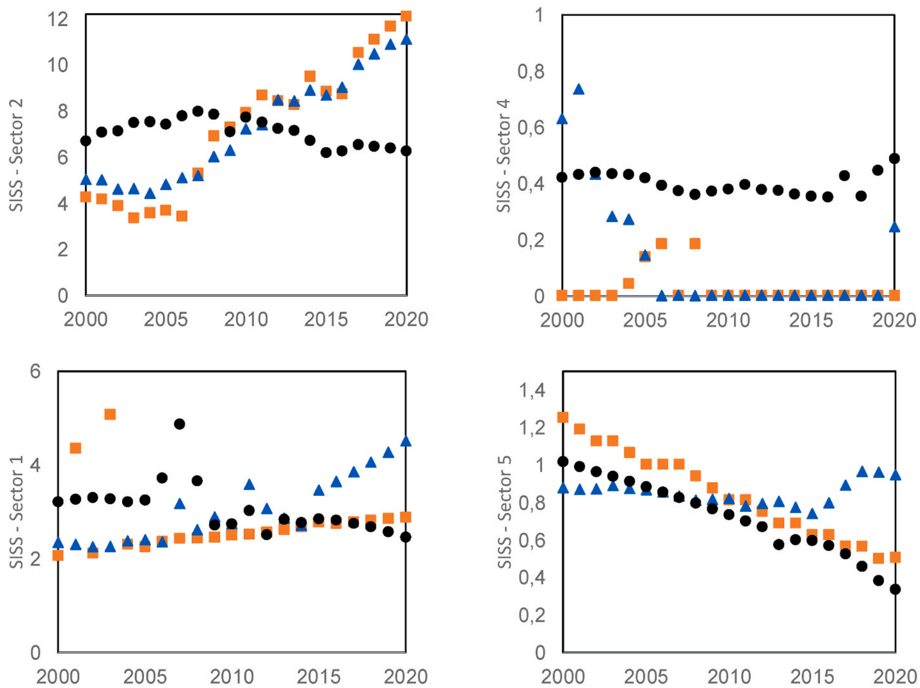

Fig. 4. Detailed results of the 5SEnSU Model for sectors 1, 2, 4, and 5 from 2000 to 2020. Lower SISS values correspond to greater proximity to the pre-defined goal and, therefore, higher sustainability. The years analyzed are on the X-axis, the SISS value on the Y-axis, and ASEAN is represented by (■), Mercosur (▲), and the European Union (●).

efficient processes facilitated access to resources and, consequently, greater exploitation than expected (Horvath et al., 2019). This phenomenon of resource depletion characterizes the "Jevons Paradox," also called the "rebound effect" or "boomerang effect" (Korhonen and Snäkin, 2015). It can thus cause unintended environmental consequences driven by the increase in general production and neutralizing the environmental benefits of CE (Zink and Geyer, 2017). Such ideas partially justify the SISS results of sector 2, and the analyzed blocks must manage their emissions more efficiently and avoid emissions occurrence.

Surprisingly, for sector 4 (K41 - Economic Openness Index and K42 - Employment Rate), the EU's SISS, except for 2000 and 2001, showed the highest SISS values and remained practically stable with only minor fluctuations in two decades. Between 2009 and 2019, ASEAN and Mercosur showed similar results. For different reasons, the differences among blocs are mainly due to the Openness Index that accounts for the trade intensity between the blocs and the rest of the world and should be maximized. The results of the ASEAN economic openness index oscillated between 0.96 and 1.07, suggesting that in this period, most of the bloc's production was traded internationally (imported or exported). For Soong (2016), China's political and economic rise helped the region develop through large financial contributions. In Mercosur, the opening index decreased, indicating lower participation of the bloc in foreign trade partially due to the lack of fiscal and monetary policies (Ferrari-Filho, 2001). The EU increased its opening index over the years but is highly dependent on imports. For Geerken et al. (2019), the relation between the openness of a country or a bloc and the potential to promote sustainability is that countries with a high percentage of imports are highly dependent on other countries, which hiders local circularity. These authors add that products not produced locally can have unintended consequences for strengthening sustainable strategies.

The indicators of sector 5 (K51 - Human Development Index and K52 - Gross National Happiness) focus mainly on the socioeconomic dimension, considering society as the recipient of the blocs functioning (Giannetti et al., 2019) since this dimension is partially related to the ability to solve or minimize people's needs. Fig. 4 shows that Mercosur had the best performance between 2000 and 2011, even showing a slight reduction in the period, but from 2016 onwards, the SISS increased continuously, and the block reached 2020 with the worst value. ASEAN had the worst indicator in 2000 but showed continuous progress over the 20 years. As for the European Union, which in 2000 occupied an intermediate position, from 2006 onwards, it started to present the best indicators in relation to the other two blocks. Regarding the HDI, the EU was the only block that reached a value above the target of 0.80 both in 2000 (0.81) and in 2020 (0.90) since the sustainability policies created a favorable environment for the production of economic and social goods influencing human development in the bloc (Kiseľáková et al., 2019). Mercosur has also improved its HDI (0.77 in 2020) and has approached the ideal value for this indicator, reflecting that, despite the barriers to more sustainable development, the bloc's countries have advanced in terms of human, economic, and social development (Reyes and Useche, 2019). In the same period, ASEAN, driven by economic growth and foreign direct investment in well-being and poverty reduction, improved from 0.61 in 2000 to 0.73 in 2020 (Ahmad et al., 2019). The SISS decrease for the EU (Fig. 4) is due to the improvement in both K51, and K52 since the EU's GNH increase may be partly related to the entry of post-communist countries into the bloc (Baltatescu, 2010), to stable economic growth and macroeconomic stability that generated greater well-being (Beja, 2017), and allowed the pursuit of happiness. In ASEAN, the SISS remained practically stable in the period. A possible explanation is presented by Yuen and Chu (2015), who, after applying empirical research using panel data and Za et al. (2021), using the multiple linear regression from 2013 to 2019, reported a negligible correlation between happiness on economic growth. Moving in the opposite direction, Mercosur showed a reduction of 6.81 in 2000 to 5.97 in 2020 due to successive economic recessions faced by the bloc, especially from 2015. According to Beja (2017), the adverse effects of a single year of recession can affect the happiness of years of economic growth.

Although the research presents convincing results on the relationship between circularity and sustainability, some limitations can be highlighted to drive advances in future studies on this topic. As it is a multicriteria method, the subjectivity inherent in the choice, the number of indicators, and weights must be presented clearly to increase objectivity and transparency. For Kujawski (2003), multicriteria models can provide conflicting classifications of alternatives for a standard set of information, even under states of certainty. Given the rarity of research on circularity and sustainability in economic blocs, future research could focus on a more extensive quantitative analysis to determine what conditions favor successful economic development, disaggregated from natural resource use and environmental impact.

5. Conclusions

In this study, the 5SEnSU and the Goal Programming philosophy made it possible to verify under different understandings and in a holistic way the relationship between circularity and sustainability, simultaneously measuring the environmental, economic, and social dimensions in ASEAN, Mercosur, and the EU between the years 2000 and 2020. The data analysis showed that circularity and sustainability are united by the common ideal of reconciling economic, environmental, and social objectives. Although it was possible to follow the EU progress toward sustainability, it was not possible to detect if the CE implementation caused profound changes over the analyzed period. The calculation of the Synthetic Indicator of Systems Sustainability allowed to verify that the EU has a superior performance towards sustainable development. Still, it was not possible to depict if this performance is due to the implementation of more advanced CE practices or the continuous application of industrial ecology, industrial ecosystems, industrial symbiosis, and cleaner production practices over the past 20 years. However, the 5SEnSu model pointed out that the impacts generated in the economic system (sector 3) of the analyzed blocks benefited social sectors (4 and 5) at the expense of environmental integrity (sectors 1 and 2). Coordinated actions are needed to reduce the use of materials and energy and release CO_2 emissions and electronic waste in all blocs.

The results clearly showed the deficiencies that appear and limit these blocs' ability to adopt a sustainable approach to further development and provide societal benefits. However, the multiplicity of metrics present in the 5SEnSU model provided important insights for policymakers to seek a balanced development across different sectors towards sustainability.

Thus, considering the monitoring frameworks that have already been launched at the Chinese level, which more broadly presented the benefits of a single system of national EC indicators, and at the European level, which sought to analyze how regions of the block differ in terms of EC implementation. Measuring progress towards circularity is a challenging factor, mainly because most existing indicators focus on the preservation of materials. Thus, it can be assumed that the different EC approaches adopted by the economic blocks influenced the SISS results. Despite the comprehensive results that simultaneously analyzed the three dimensions of sustainability, the study has limitations based on the data used. Given the rarity of research on circularity and sustainability in economic blocs, future research could focus on a more extensive quantitative analysis to determine what conditions favor successful economic development, disaggregated from natural resource use and environmental impact.

CRediT authorship contribution statement

Luiz C. Terra: Data curation, Writing – original draft. **Biagio F. Giannetti:** Methodology, Jan Jansen. **Feni Agostinho:** Methodology, Writing – review & editing. **Cecilia M.V.B. Almeida:** Conceptualization, Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132890.

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