Journal of Circular Economy
https://doi.org/10.55845/YTGD9041 Volume 3, Issue 1

Research paper

A Novel Framework to Measure Circularity Trade-offs and Synergies in the Global Context

Glenn A. Aguilar-Hernandez[1 2 *]

Handling Editor: Roberto Minunno

Received: 25.11.2024 /Accepted: 15.05.2025

Abstract

A growing attention has been given to understanding the social, economic and environmental impacts of circular economy (CE) strategies at national and regional levels. However, the potential trade-offs and synergies involved in a CE transition remain underexplored. This paper presents a novel framework designed to measure these trade-offs and synergies through three key dimensions: impact, geography, and sector. This step-wise, multi-dimensional approach enables a detailed analysis of circularity challenges and benefits. To illustrate the framework's application, a hypothetical scenario was developed on CE strategies within the agriculture sector, focusing on trade-offs and synergies between two regions — the European Union and Latin America & the Caribbean. This framework contributes to a better understanding of potential winners and losers in a global circularity transition, and supports policymakers in interpreting CE scenarios effectively.

Keywords: Circular Economy Scenarios · Trade-offs and Synergies · Multi-Criteria Decision Analysis · Triple-Botton-Line · Data Envelopment Analysis · Nexus Global North and South

Abbreviation List

BAU	Business-As-Usual Scenario
CES	Circular Economy Scenarios
DEA	Data Envelopment Analysis
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas emissions
LAC	Latin America and the Caribbean
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDA	Multi-Criteria Decision Analysis
MR EEIOA	Multi-Regional Environmentally Extended Input-Output Analysis
TBL	Triple-Bottom-Line
VA	Value Added

[1] Institute of Environmental Sciences (CML), Leiden University, The Netherlands
[2] Academia de Centroamérica, Costa Rica
[*]Corresponding author: g.a.aguilar.hernandez@cml.leidenuniv.nl

©The Author(s) 2025

1. INTRODUCTION

Circular economy scenarios (CES) have contributed to understanding the potential social, economic and environmental implications of a circularity transition on a country and global scale (McCarthy et al., 2018). Several researchers have identified potential trade-offs within circularity strategies (Ross et al., 2023; Safarzynska et al., 2023). For example, an increase in recycling activities in Europe could potentially create more sources of employment in European countries while reducing job creation in middle- and lower-income countries (e.g., in South East Asia and Latin America) (Wiebe et al., 2019). Although several CES result in potential trade-offs and synergies, there is still a lack of understanding about who would be the winners and losers of a global circularity transition, and how to assess synergies and trade-offs systematically.

Several frameworks have been developed to identify trade-offs and synergies. For example, the application of Multi-Criteria Decision Analysis, Data Envelopment Analysis, and Triple-Bottom-Line approaches has facilitated the identification of trade-offs between social, economic and environmental impacts of multiple systems (Hacking & Guthrie, 2008; Huang et al., 2011; Sala et al., 2015). Multi-Criteria Decision Analysis (MCDA) has its roots in operational research and decision engineering, providing a systematic framework for evaluating alternatives based on multiple criteria to inform decision-making processes, allowing to explore potential trade-offs and synergies within multiple alternatives (Cinelli et al., 2020). With modern applications, MCDA has evolved since its beginnings, and played a prominent role in decision-making processes, including in policy-related questions (Belton & Stewart, 2002). In general, MCDA involves three core components: identifying alternatives, establishing criteria, and generating recommendations (Belton & Stewart, 2002). A notable feature of MCDA is its interactive nature, which integrates stakeholders throughout the process, enabling a more robust decision-making environment.

Triple-bottom-line (TBL) considers three fundamental dimensions of sustainability: economy, society, and environment (Hacking & Guthrie, 2008). Widely utilized for evaluating and reporting socio-economic and environmental impacts across various scales—from business operations to national policies—TBL incorporates a distinctive feature of benchmarking to facilitate comparative analysis of multiple indicators and longitudinal monitoring of a system (Vanclay, 2004). From a macro-level perspective, several studies have applied TBL principles to assess socio-economic and environmental performances of different economies (Onat et al., 2014; Scherer et al., 2018; Veiga et al., 2018). This approach enables the identification of trade-offs across multiple indicators. For instance, Wiebe et al. (2023) implemented TBL concepts to evaluate the impacts of CE strategies in the Norwegian economy across multiple sectors (e.g., textile, plastics, construction).

Data Envelopment Analysis (DEA) is used to assess the efficiency of processes or systems by considering inputs as positive or beneficial aspects and outputs as negative aspects (Cook & Seiford, 2009). This approach distinguishes between positive and negative parameters of decision-making processes, facilitating the identification of potential trade-offs within operations (Mcwilliams et al., 2016). DEA is an optimization approach, typically involving linear programming to either maximize or minimize the operation of a systems. Furthermore, DEA has been applied across various levels, from analyzing business strategies to nation-wide assessments (Fan & Fang, 2020; Mardani et al., 2017; Wang et al., 2021).

Within the context of CE research, Quintelier et al. (2023) recently proposed a mixed-method framework that integrates stakeholder theory to examine trade-offs, synergies, and strategic decision-making in CE transitions. However, a significant research gap remains, as there is currently no systematic approach to comprehensively measure trade-offs and synergies in CE strategies, particularly when considering both direct and indirect impacts of a global circularity transition. Addressing this gap is essential to developing more effective policies and decision-making frameworks for CE implementation.

In this paper, I propose a novel framework for measuring trade-offs and synergies of circular economy strategies on a macro-scale[3]. The framework provides three key dimensions—geographical, impacts, and sectoral—that allow for the identification of winners and losers from a multi-dimensional perspective. This is the first framework that allows for the identification and assessment of trade-offs and synergies of multiple circularity strategies in a

[3] A preliminary version of this study was presented at the Special Session on Advances in Circular Economy Scenario Modelling at the 30th International Input-Output Association Conference on July 2nd, 2024 (in Aguilar-Hernandez, 2024). This article provides a restructured framework, a new scenario analysis, detailed discussion, and a broader scope, incorporating feedback from the conference session.

systematic way. This work contributes to facilitating the interpretation of CES modeling and support decision-making in CE policies.

This paper is organized as follows: Section 2 provides an overview of the existing literature on circularity trade-offs and synergies, highlighting the key dimensions—geographical, impacts, and sectoral—that form the basis of the proposed framework. It also presents the framework in a step-wise manner and introduces an hypothetical CE scenario to illustrate its application. Section 3 presents the results from the illustrative case study and discusses the key aspects of the framework, including its strengths, limitations, and practical implications for decision-makers. Finally, Section 4 provides concluding remarks, outlining future research directions.

2. METHOD

Firstly, the key dimensions of circularity trade-offs and synergies were defined through a literature review (in Section 2.1). Then, a step-wise framework was created, incorporating algebraic expressions to identify trade-offs and synergies systematically (see Section 2.2). Lastly, a Python code was developed to facilitate the quantification of trade-offs and synergies, which is illustrated with an illustrative scenario measuring the potential trade-offs and synergies between the European Union (EU) and Latin America and the Caribbean (LAC) under the assumptions of implementing CE strategies in the LAC agricultural sector (see details in Section 2.3).

2.1 Circularity Trade-Offs and Synergies

In the context of CE policies, trade-offs and synergies are crucial aspects for understanding the dynamics of CE strategies within systems (e.g., industries, countries, or regions). Trade-offs occur when CE strategies positively affect one part of a system while negatively impacting another part, creating 'win-lose' situations, whereas synergies arises when CE strategies have positive effects on multiple parts of a system, leading to 'win-win' situations (OECD, 2022). Likewise, losses occur when parts of a system are negatively impacted, generating ‘lose-lose’ situations.

After analyzing over 300 Circular Economy Scenarios (CES) at macro level, it has been shown that circularity synergies are more prevalent within isolated countries, particularly in terms of changes in Gross Domestic Product (GDP), job creation, and greenhouse gas (GHG) emissions (Aguilar-Hernandez et al., 2021). However, considering broader systems shows potential for trade-offs across multiple dimensions, requiring a structural assessment of circularity trade-offs and synergies (OECD, 2022; Quintelier et al., 2023). Moreover, it is essential to define the main dimensions for assessing circularity trade-offs and synergies. Here, three key dimensions emerge from previous CE modelling studies: impacts, geographical, and sectoral dimensions (see summary in Table 1).

The impacts dimension refers to the effects of CE strategies across various impact indicators. These indicators encompass social aspects (e.g., employment and occupational health and safety), economic factors (e.g., cost and changes in value added), and environmental considerations (e.g., materials, energy, water, and GHG emissions) (Moraga et al., 2019; Padilla-Rivera et al., 2021). For instance, CE implementation in the EU is estimated to boost GDP by €900 billion and reduce GHG emissions by 50% by 2030, exemplifying a 'win-win' scenario (SYSTEMIQ & Ellen Macarthur Foundation, 2017). However, such economic gains do not always translate into proportional environmental benefits. Mohsin et al. (2024) analyzed the relationship between GDP growth and CO_2 emissions in EU countries, revealing that a 1% increase in real GDP corresponds to a 1.1% rise in CO_2 emissions. This finding suggests that highly industrialized economies within the EU may struggle to fully decouple economic growth from environmental impact, emphasizing the need for targeted CE policies to mitigate unintended consequences.

The impact dimension is commonly assessed in Life Cycle Assessments (LCA) and Life Cycle Costing (LCC) studies, identifying trade-offs and synergies within environmental and economic indicators, respectively (Merli et al., 2018; Sassanelli et al., 2019). Luthin et al. (2024) assessed the recycling of carpet tiles containing recycled and bio-based materials, finding that while global warming potential was reduced, trade-offs emerged in the form of acidification and increased operational costs for recycling facilities. Similarly, Sasso et al. (2024) demonstrated that integrating CE activities within lean manufacturing can enhance environmental performance, operational efficiency, and competitive advantage, further reinforcing the strategic value of circularity.

The geographical dimension examines the macro level effects of CE implementation across multiple countries or regions within specific impact indicators. For instance, this perspective allows for an assessment of whether CE strategies in the Global North generate shared economic benefits across both Northern and Southern regions. Schroeder et al. (2018) highlighted that potential trade-offs may arise between countries when global value chains shift, influencing how economic gains and losses are distributed. However, this dimension remains relatively underexplored, despite the growing use of macro-level modeling approaches such as Multi-Regional Environmentally Extended Input-Output (MR EEIO) models, Computable General Equilibrium (CGE) models, and Integrated Assessment models, which facilitate the analysis of cross-regional impacts (Rietveld et al., 2021). For instance, when assessing employment as a social indicator, CE scenario modeling using MR EEIO models suggests that a global implementation of CE strategies could lead to a 2.7% increase in employment within the EU, while in Asian economies, employment could decline by 2.6%, creating a 'win-lose' scenario across regions (Wiebe et al., 2019).

More recently, Repp et al. (2021) pointed out that employment could significantly decline in low- and middle-income countries outside the EU, particularly in labor-intensive sectors, exacerbating existing economic disparities. Furthermore, Safarzynska et al. (2023) explored the leakage effect of CE implementation—where industries relocate from developed to developing countries due to stringent environmental policies that increase production costs in developed nations. Their findings suggest that such relocations could also affect metal-intensive industries, potentially offsetting the intended CE benefits within the EU. Moreover, the Global Resource Outlook 2024 (UNEP, 2024) provided global CE scenarios showing that while GHG emissions reductions could be achieved across low-, middle-, and high-income regions, regional disparities in environmental benefits persist. This emphasizes that 'win-win' outcomes are not equally distributed across regions, highlighting the need for context-specific CE policies to ensure more equitable CE transitions.

Zooming into supply chains, the sectoral dimension examines the trade-offs and synergies that emerge across different industries when CE strategies are implemented. CE transitions can create significant shifts in employment and economic activity, benefiting some sectors while challenging others. For instance, secondary-based metal production, services, and the recycling sector are expected to experience strong job creation, whereas primary materials extraction and materials-intensive industries may face job reductions (Bibas et al., 2021; Chateau & Mavroeidi, 2020).

Recently, Verma et al. (2024) identified key industries within the food-water-energy nexus (e.g., agriculture, energy, water irrigation, and treatment industries), highlighting that trade-offs and synergies occur throughout the supply chain, influencing both resource efficiency and economic stability. Similarly, Romero et al. (2024) examined the case of Argentina’s recycling sector, showing that while the replacement of virgin materials and fossil fuels generates over 8000 new jobs in circular activities jobs, it also results in around 5500 job losses in traditional primary material sectors. These effects extend throughout the entire supply chain, producing both direct and indirect employment shifts.

Beyond employment, CE policies can also reshape market incentives. The OECD report (2022) on Synergies and Trade-offs emphasized that CE strategies, particularly those disincentivizing primary material use, can reduce environmental impacts but may have negative economic consequences for material-intensive sectors. Understanding trade-offs and synergies at the sectoral level provides a valuable opportunity to engage with affected industries and develop strategies to mitigate potential losses, ensuring a more just CE transition.

Table 1. Summary of Circularity Trade-Offs and Synergies Dimensions

Dimension	Description	References
Impact	Examines the social, economic, and environmental effects of CE strategies, highlighting trade-offs and synergies across different indicators.	Luthin et al. (2024) Merli et al. (2018) Mohsin et al. (2024) Sassanelli et al. (2019) Sasso et al. (2024)
Geographical	Analyzes effects of CE strategies across multiple countries or regions, assessing economic and environmental benefits or disparities caused by global value chain shifts.	Repp et al. (2021) Safarzynska et al. (2023) Schroeder et al. (2018) UNEP (2024) Wiebe et al. (2019)
Sectoral	Investigates how CE strategies affect different industries, creating employment shifts, supply chain disruptions, and economic consequences.	Bibas et al. (2021) Chateau & Mavroeidi (2020) OECD (2022) Romero et al. (2024) Verma et al. (2024)

2.2 Trade-Offs and Synergies Framework

Considering the multi-dimensional aspects of circularity trade-offs and synergies, a novel framework is proposed here as a systematic approach to identify and assess the 'winners' and 'losers' of a specific CE strategy. This framework, comprising four main steps, serves as a guideline for systematically evaluating CE strategies (see Figure 1).

2.2.1 Step 1: Scenario Analysis

Developing scenarios is the first step to assess potential circularity synergies and trade-offs. From macro-level perspective, there are multiple models that allow to quantity impacts of the CE strategies (McCarthy et al., 2018; Rietveld et al., 2021; Towa et al., 2021). As mentioned above, MR EEIOA, CGE and Integrated Assessment models are some of the core models to assess potential social, economic, and environmental impacts of a circularity transition (Aguilar-Hernandez et al., 2021). For the proposed framework, any macro-level model that quantify economic, social, and environmental indicators between different countries and sectors can be applied.

As an example for illustrative purposes, Multi-Regional Environmentally Extended Input-Output Analysis (MR EEIOA) is used as basis for the scenario analysis. MR EEIOA provides a comprehensive approach to assess inter-industry interactions across multiple regions or countries. This approach allows to measure the direct and indirect impacts of economic activities across multiple sectors and regions, enabling the calculation of embodied impacts—such as carbon and material footprints, resource use, and embodied employment effects—from final demand, bringing the consumption-based perspective on CE impacts (Wood et al., 2015). A key feature of EEIOA is the Leontief inverse (see Equation [1]), which captures the cascading effects of economic transactions, allowing for the estimation of upstream and downstream impacts across supply chains (Miller & Blair, 2009). While MR EEIOA is used here as an example for scenario analysis, the proposed framework is flexible and can integrate other modelling approaches, such as CGE or Integrated Assessment models, as long as they provide indicators reflecting the multi-dimensional aspects of CE strategies.

Considering a macro-level model, Circular Economy Scenarios (CES) represent the anticipated changes resulting from circularity strategies and can be compared against a Business-As-Usual (BAU) scenario to highlight structural changes. For example, in a MR EEIOA, CES can be expressed by changing parameters in the intermediate and final demand of specific economic sectors within a country/region (Rietveld et al., 2021; Towa et al., 2021). Algebraically, CES can be estimated in a MR EEIO system as:

$$CES_i = \hat{b}_i^* x^* = \hat{b}_i^* (I - A^*)^{-1} y^* \quad [1]$$

where, x^* represents total output of the respective circularity interventions, $\hat{b}_i$ represents the diagonalized vector of impact i (e.g., value added, total employment, GHG emissions per unit of output), $(I - A^*)^{-1} = L^*$, denotes the modified Leontief inverse, and y^* is for the modified final demand vector (Çetinay et al., 2020). In a general MR EEIO system, CES_i has a dimension of $n \times 1$, with $n = number\ of\ sectors\ \times number\ of\ countries$. Business-as-usual (BAU) vector can be calculated using equation [1] without any modifications in b, A or y (Donati et al., 2020). These algebraic expressions are well-known and used by researchers on the EEIOA field (McCarthy et al., 2018; Rietveld et al., 2021; Towa et al., 2021).

2.2.2 Step 2: Data Harmonization

Data harmonization involves normalizing CES impacts compared to the BAU scenario. This process assigns relative values to CES impacts, considering both their magnitude and direction. The normalization vector (N_i) is expressed as the relative value of the difference of between CES and BAU scenarios as:

$$N_i = \frac{(CES_i - BAU_i)}{\sum_{k=1}^{n} BAU_{k,i}} \times 100 \ [2]$$

The normalization vector N_i is divided by the sum of all the BAU scenarios in order to provide the share of each individual CES impact respect to the overall impact, which is common application of normalizing factors in MCDA approaches (see, for example, Cinelli et al., 2022).

As part of data harmonization, it is crucial to develop a sign harmonization. This ensures consistent interpretation of positive and negative values across economic, social, and environmental indicators. For instance, a 'win' situation for changes in GDP would imply positive values of N_{GDP} elements, while a 'win' situation for environmental dimension would be a reduction of GHG emissions represented as negative values of N_{GHG} elements. In this paper, a 'win' is interpreted as $N_i > 0$; a 'lose' as $N_i < 0$, and a 'tie' as $N_i = 0$. However, sign allocation can be changed by practitioners when applying this framework as long as it is defined, and used consistently throughout Step 3 and 4.

As in most of the cases environmental indicators are considered 'wins' if there is a reduction of environmental impacts in CES compared with BAU. This implies a sign harmonization when comparing economic and environmental indicators such as value added and GHG emissions. Thus, signs should be changed for those indicators where 'win' and 'lose' situation are the opposite (see Table 2).

Table 2. Sign harmonization according to 'win' or 'lose' situations

Impact dimension	Indicator (example)	Win situation	Lose situation	Sign harmonization
Economic	Value added, VA	$N_{VA} > 0$	$N_{VA} < 0$	$N_{Va}^{SH} = N_{VA}$
Social	Employment, Emp	$N_{Emp} > 0$	$N_{Emp} < 0$	$N_{Emp}^{SH} = N_{Emp}$
Environmental	GHG emissions, GHG	$N_{GHG} < 0$	$N_{GHG} > 0$	$N_{GHG}^{SH} = -(N_{GHG})$

It is important to note that sign harmonization can be implemented in other dimensions, although it is most commonly applied to environmental impacts. For example, when economic costs or debts are used as economic indicators, a 'win' situation would correspond to a reduction in such indicators. Thus, Table 2 should be modified accordingly to reflect this in the economic dimension. For illustrative purposes, the rest of the paper will use the sign harmonization as presented in Table 2. Furthermore, sign harmonization requires the inclusion of stakeholders to decide which changes in impacts are considered a 'win' or 'lose' situation. In general, it is expected a 'win-win' when increasing socioeconomic impacts while reducing environmental impacts, but it might vary depending on the indicators. Thus, the application of MCDA procedures can contribute to include stakeholders' views as part of the eligibility criteria, enhancing the framework.

2.2.3 Step 3: Concatenating Dimensions

The harmonized CES vectors are concatenated to form a trade-offs, synergies, and losses matrix (TSL), which integrates the impact, geographical, and sectoral dimensions. Each element of TSL corresponds to a specific sector within a country, and the harmonized impacts. TSL matrix is generated by concatenating each harmonized vector, as follows:

$$TSL = [N_1^{SH}|N_2^{SH}|\cdots|N_m^{SH}] \quad [3]$$

Here, TSL has m blocks of N_i^{SH} vectors concatenated horizontally. In a matrix system – such as in MR EEIO system – TSL contains sectors s per country c in rows, and harmonized impacts i in columns, which means that each element of TSL covers the three circularity trade-offs and synergies dimensions.

By arranging data points in a cardinal system, trade-offs and synergies can be easily visualized, facilitating further analysis. For instance, when considering two dimensions, A and B, the TSL matrix is structured within a cardinal system, enabling easy identification of trade-offs and synergies. In a two-dimensional analysis, data points are compared to identify 'win-win' situations as synergies, 'win-lose' or 'lose-win' scenarios as trade-offs, and 'lose-lose' outcomes as losses (see Figure 1). This interpretation follows the principles considered by several trade-offs and synergies studies (see, for example, Haase et al., 2012). Likewise, a multi-dimensional analysis can be developed by following the same structure, considering a clear interpretation of trade-offs, synergies and losses in each analysis.

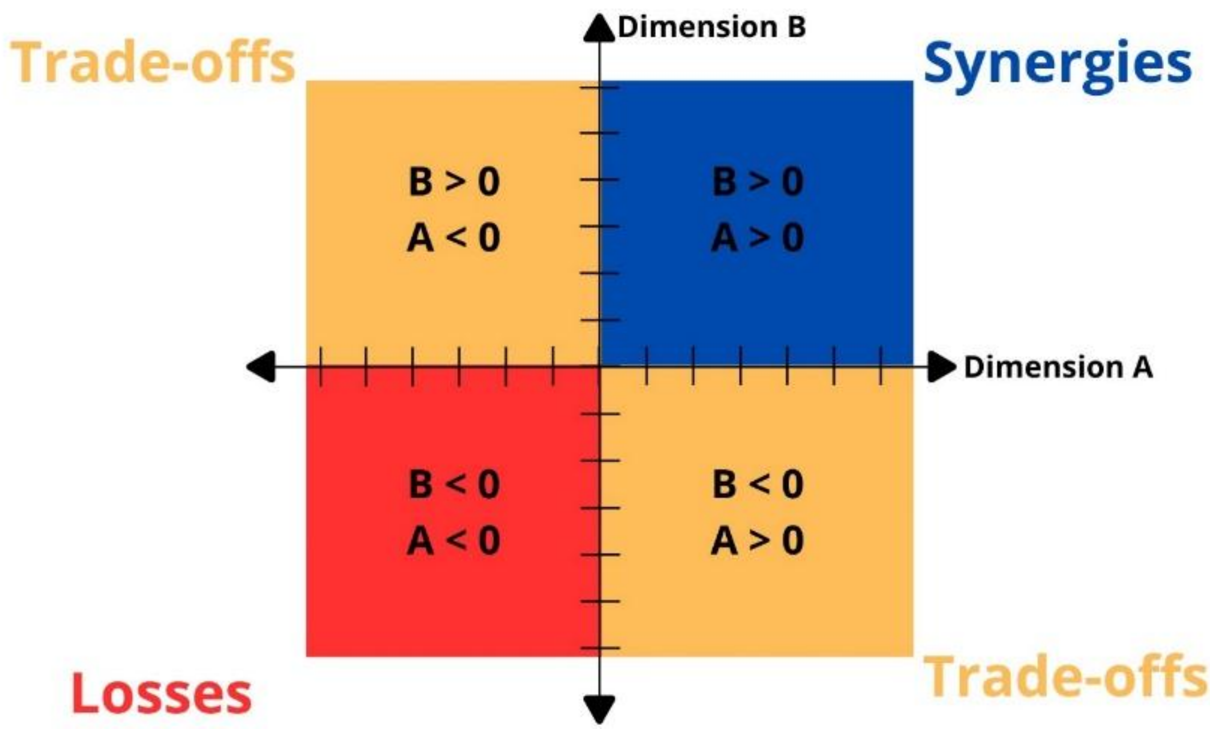

Figure 1. Diagram of Trade-Offs, Synergies and Losses for Two Dimensions A and B. Synergies (in blue quadrant) are 'win-win' situations, trade-offs (in yellow quadrant) are 'win-lose' and 'lose-win', losses (in red quadrant) are 'lose-lose' situations

2.2.4 Step 4: Trade-Offs and Synergies Analysis

Finally, the magnitude of trade-offs, synergies and losses are quantified by using an Euclidean approach. Similar to methods used for calculating Decision Making Unit in DEA approaches (see, for example, Ezici et al., 2020), the overall magnitude of circularity trade-offs and synergies (v) is estimated by:

$v = \sqrt{(tsl_{dim-1})^2 + (tsl_{dim-2})^2 + \cdots + (tsl_{dim-n})^2}$ [4]

where tsl_{dim-n} represents the elements of TSL for n dimensions. For example, considering a trade-offs and synergies analysis for dimension A and B, in which the A element is a 'lose' situation with $a = -0.4$, and the B element is a 'win' situation with $b = 0.5$. This means that there is a trade-off between dimension A and B as a 'lose-win' situation. Following equation [4], the magnitude of this trade-off is $v_{A,B} = \sqrt{(tsl_A)^2 + (tsl_B)^2} = \sqrt{(-0.4)^2 + (0.5)^2 = 0.64}$. Figure 2 shows a graphical representation of quantifying trade-offs and synergies.

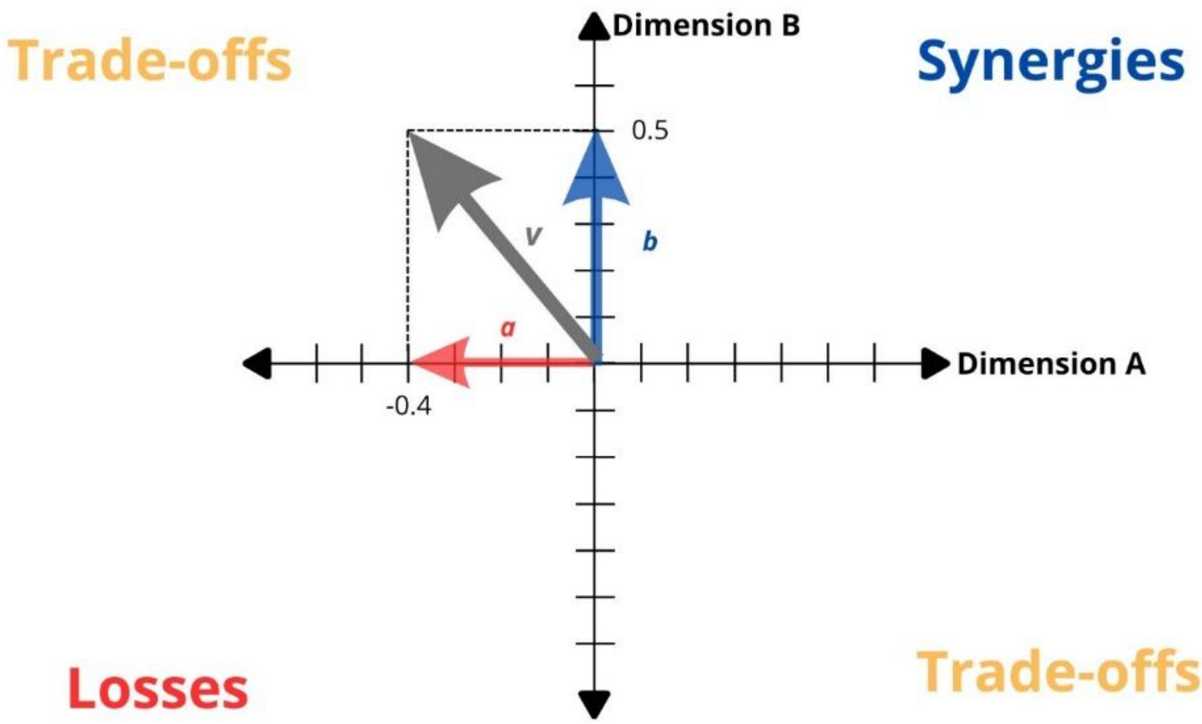

Figure 2. Example of Magnitude of Trade-Offs, Synergies and Losses for Dimension A and B

The Euclidean sum offers a comprehensive means to analyze multiple dimensions simultaneously, thereby providing a convenient method for assessing overall circularity trade-offs and synergies. When dealing with numerous data points across dimensions—such as examining GHG emissions in multiple sectors across two regions—this approach allows for the aggregation of trade-offs, synergies, and losses into a single measure, as follows:

$v_{sum} = \sum_{k=1}^{w} v_k$ [5]

where v_k represents each Euclidian vector for w number of data points. The magnitude v_{sum} serves as an aggregate indicator that enables comparisons between different CE scenarios. A higher v_{sum} value suggests a greater overall synergy, trade-off or losses effect, meaning that the scenario introduces more significant positive and/or negative impacts across dimensions. Conversely, a v_{sum} value suggests that the trade-offs and synergies are more balanced or have a lower overall intensity.

For example, suppose two CE strategies are being compared:

- Scenario A: Reducing waste to landfill through stricter landfill bans and improved waste separation, with an Euclidian sum v_{sum-A}.
- Scenario B: Increasing remanufacturing by expanding infrastructure and integrating remanufactured components into supply chain, with an Euclidian sum v_{sum-B}.

If $v_{sum-A} > v_{sum-B}$, this suggests that the waste reduction strategy generates larger overall trade-offs and synergies than the remanufacturing activities. This could mean that Scenario A has stronger positive impacts (e.g., lower emissions, reduced resource extraction) but also greater trade-offs (e.g., higher costs, job losses in treatment sector). Meanwhile, Scenario B, despite requiring initial investment in remanufacturing facilities and technological adaptation, may lead to more stable economic benefits, such as job creation in high-value recovery industries. Thus, v_{sum} does not determine which scenario is 'better' or 'worse' but rather provides a decision-support tool to help policymakers assess which strategy aligns best with their priorities.

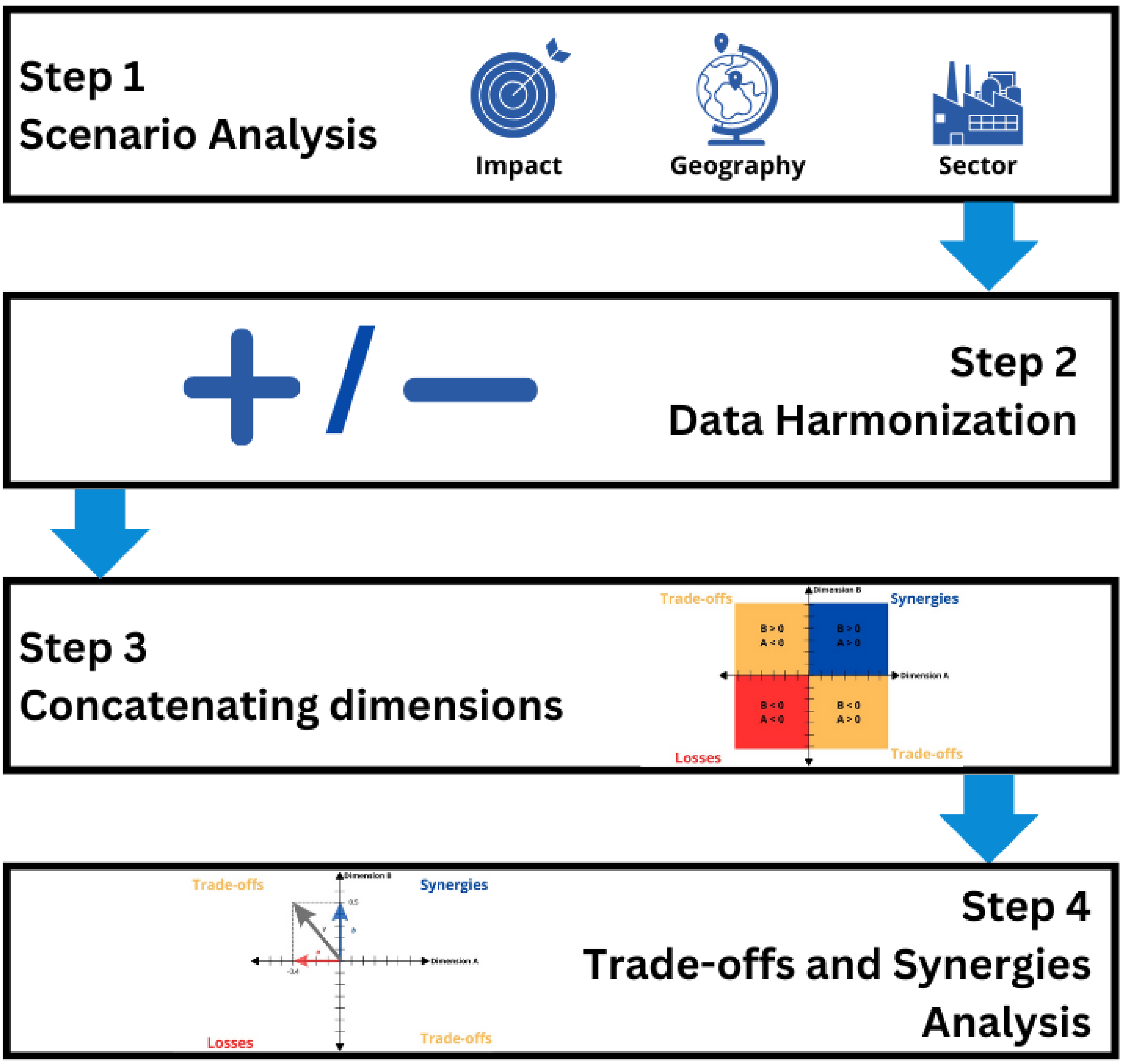

Figure 3. Diagram of Proposed Trade-Offs and Synergies Framework

2.3 Illustrative Example and Data

2.3.1 Scenario Setting and Assumptions

To illustrate the application of the proposed framework, this study conducts a circularity trade-offs and synergies analysis focusing on Latin America & the Caribbean (LAC) and the European Union (EU).

LAC plays a critical role in global supply chains, particularly in biomass production, which includes agricultural and forestry products (Coalition of Circular Economy from Latin America & Caribbean, 2022). Currently, the region has around 40% of biomass potential that could be recovered through CE strategies (Circle Economy, 2023). At the same time, biomass waste remains a significant environmental challenge. For instance, in food production and consumption, LAC generates around 2 tonnes per capita of food loss and waste per year, which represents approximately 15% of its food availability (Costa et al., 2024; FAO, 2014).

As the CE transition gains momentum, multiple LAC countries have started implementing CE policies (Samaniego et al., 2022). To date, 11 countries have developed national strategies and roadmaps, focusing on key economic sectors such as agriculture, mining, manufacturing, and construction (Aguilar-Hernandez et al., 2024; Gallego-Schmid et al., 2024). Within the agricultural sector, regenerative agricultural practices have emerged as a core CE strategy, aiming to replace chemical fertilizers with composted biomass waste and promote organic production (Gallego-Schmid et al., 2024). For instance, Colombia has set a target to utilize 20% of its total biomass production for CE purposes by 2030 (MinAmbiente, 2019), while Chile aims to repurpose 40% of biomass and recycled materials by 2040 (MMA, 2020).

Within this context, the modeled scenario assumes that the LAC region implements regenerative agricultural practices as part of its CE strategies, while the EU increases its demand for circular agricultural products from LAC. The specific interventions modeled include:

1. Reducing the use of chemical fertilizers: A 30% reduction in chemical fertilizer supply, including both domestic production and imports, in the LAC agricultural sector and final demand. This value is based on the average biomass recovery target set by Colombia (20%) and Chile (40%) for 2030.
2. Increasing organic composting as a substitute: A corresponding increase in the supply of organic compost in the LAC agricultural sector and final demand, replacing the reduced fertilizer use. The amount of organic compost supplied is determined based on the monetary savings from fertilizer reduction, assuming a reallocation of agricultural and final demand spending.
3. Higher EU demand for circular agricultural products from LAC: An increase of 30% in EU imports of LAC agricultural and food products, driven by a growing EU market preference for circular food products.

This is a hypothetical counterfactual scenario, meaning it is not a prediction but an exploratory analysis for illustrative purposes. The objective is to assess how the proposed interventions in the LAC agricultural sector could influence both LAC and EU economies under CE scenarios, identifying potential 'winners' and 'losers'. Overall, the assumptions do not introduce radical economic changes, which mean that modelling results are assumed to be marginal changes, which are sufficient to show the applicability of the proposed framework.

2.3.2 Data

For this example, I applied the MR EEIOA model developed by Donati et al. (2020), using the Input-Output table, industry-by-industry for 2020 from EXIOBASE v3.9.5 (available at: https://zenodo.org/records/14869924). In the MR EEIOA field, updating datasets is often challenging due to the complexity of data collection and computational constraints (Wiedmann et al., 2011), although recent advancements have improved this process. As a result, a five-year gap between available datasets is common, and the 2020 data represents one of the most up-to-date datasets currently accessible. While this poses some limitations for scenario analysis, it is important to note that structural changes in the economy typically unfold over decades rather than short periods (Wiedmann et al., 2011). Thus, assuming no radical economic shifts at the global scale remains a reasonable assumption for the analysis.

EXIOBASE v3.9.5 contains 163 industries across 44 countries and 5 rest of the world regions, along with 9 economic factors of production, 7 consumption categories, and 728 social and environmental indicators. To simplify the model for illustrative purposes, the dataset was aggregated into: 3 world regions (i.e., LAC, EU, and Rest of the World), 10 industries including agriculture, chemical fertilizers, composting, manufacturing, and services (full list in ‘data input (aggregated) + assumptions’ file, Supplementary Information), 1 factor of production (i.e., value added), 1 consumption category (i.e., final demand), and 2 social and environmental indicators (i.e., employment and GHG emissions). The aggregation procedure and modeling were conducted using MARIO software (Tahavori et al., 2023). The aggregated Input-Output table used in this study is available in the ‘data input (aggregated) + assumptions’ file, Supplementary Information.

Considering EXIOBASE v3.9.5 as data inputs, the scenario analysis incorporated changes in inter-industries coefficients and final demand following the assumptions described in Section 2.3.1. Then, the key dimensions—geographical, impact, and sectoral—were analyzed in terms of the final demand of each aggregated region. EU member countries were aggregated into a single EU region, while LAC encompassed Mexico, Brazil, and the remainder of Latin America and the Caribbean, following EXIOBASE country-region classification.

The geographical dimension was selected as an illustrative example of Global North-South interactions, highlighting potential trade-offs and synergies between developed and developing economies. However, this framework can be applied to any regional grouping, depending on the scope of the analysis and the specific research questions being addressed.

Regarding the impact dimension, this case study focuses on value added (measured in million euros) as an economic indicator, employment (in thousand people) as a social indicator, and GHG emissions (in tonnes CO_2 equivalent) as an environmental indicator. In EXIOBASE v3.9.5, emissions data includes 413 distinct pollutants, of which six are classified as greenhouse gases (GHGs) from combustion processes: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). These GHG emissions were converted into CO_2-equivalent (CO_2 eq) by multiplying the GHG emissions values with their respective Global Warming Potential (GWP-100) values from the IPCC AR6 report (Minx et al., 2022) (see full method in Python code, Supplementary Information). For 2020, the total GHG emissions in CO_2 equivalents from EXIOBASE v3.9.5 were estimated at 35.6 gigatonnes CO_2 eq, which aligns closely with the 35.9 gigatonnes CO_2 eq from combustion reported by the IPCC for the same period (Minx et al., 2022).

The sectoral dimension considers changes in the chemical fertilizers and composting sectors, as these are the key industries involved in the scenario analysis (as described in Section 2.3.1). In all three dimensions, it is crucial to account for both direct and indirect impacts of CE strategies when identifying ‘winners’ and ‘losers’ to determine whether a particular CE implementation yields net benefits. This highlights the importance of employing models such as MR EEIOA, which enable the quantification of embodied impacts (i.e., footprints) across these dimensions (Della Bella et al., 2023; Donati et al., 2020; Towa et al., 2021). By integrating MR EEIOA, researchers can comprehensively evaluate the ripple effects of CE strategies, facilitating the interpretation of their potential outcomes and informing decision-making processes.

The framework was presented during the Special Session on Advances in Circular Economy Scenario Modelling at the 30th International Input-Output Association Conference (see Aguilar-Hernandez, 2024). The session gathered 35 experts in macroeconomic modeling who provided valuable feedback on the approach. Overall, the framework and algebraic expressions (in Section 2.2) were well-received. One suggested improvement was to consider using MR EEIO databases other than EXIOBASE. Despite these limitations, EXIOBASE was selected due to its high level of geographic and sectoral resolution (e.g., secondary material production in the 49 countries/regions), which is essential for testing the multi-dimensional aspect of this framework. Furthermore, as the hypothetical scenario is mainly illustrative, the use of EXIOBASE does not impact the framework’s usability. As mentioned in Step 1 - Scenario Analysis, the framework can be adapted to any model that enables multi-dimensional scenario assessments.

A summary of data inputs and assumptions is available in ‘data inputs + assumptions’ file, in Supplementary Information. Further details, including scenario analysis, results and Python code, are available at the DOI 10.5281/zenodo.15223878

3. RESULTS AND DISCUSSION

3.1 Circularity Trade-Offs and Synergies From Implementing CE Strategies in the LAC Agricultural Sector

Considering the suggested CE scenario (in section 2.3.1), the following section presents the potential trade-offs, synergies, and losses that could occur in the LAC and EU social, economic and environmental footprints from implementing CE strategies in the LAC agricultural sector.

Figure 4 presents the aggregated results showing changes in value added, employment, and GHG emissions footprints resulting from the implementation of the CE scenario (outlined in Section 2.3.1). Under the CES assumptions, the overall impact on the EU would include a 0.03% increase in value added, a 0.29% rise in employment, and a 0.30% reduction in GHG emissions (adjusted to +0.30% following sign harmonization). Meanwhile, in LAC, the scenario leads to a 0.04% reduction in value added, a 0.01% increase in employment, and a 2.96% rise in GHG emissions compared to the Business-as-Usual (BAU) scenario.

While CE strategies are generally expected to reduce GHG emissions, this scenario shows that substituting chemical fertilizers with organic alternatives leads to higher embodied emissions for the LAC final demand. This finding aligns with existing literature, which suggests that chemical fertilizers contribute significantly to nitrous oxide emissions, while organic fertilizers derived from biomass can generate larger amounts of CO_2 and methane (He et al., 2023). However, the scenario analysis does not account for feedback loops or the fact that organic matter originates from renewable sources, contributing to a closed carbon cycle. Moreover, the GHG emissions produced by organic composting would still occur if the biomass were wasted in landfills, but in that case, it would provide no added value to the economy. Thus, the results from this hypothetical scenario should be interpreted with caution, as they do not capture the full complexity of carbon dynamics and long-term system interactions.

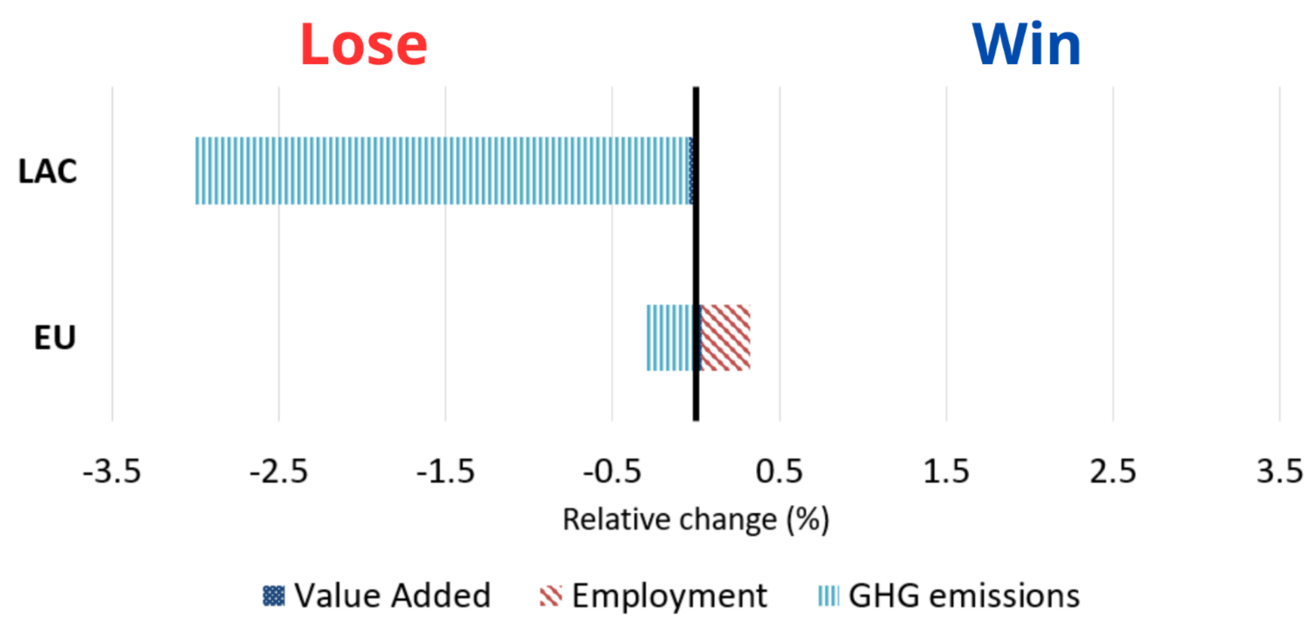

Figure 4. Relative Changes in Normalized Value Added, Employment and GHG Emissions from the EU and LAC Circular Economy Scenarios in the Construction Sector. Relative negative changes represent a 'lose' situation, while relative positive changes represent a 'win' situation

Concatenating dimensions (i.e., step 3) enables a detailed identification of where trade-offs, synergies, and losses occur. For instance, Figure 5 shows the relationship between GHG emissions footprint for LAC and the EU final demand, with each data point representing the changes in GHG emissions footprint per sector, encompassing 10 aggregated sectors from a total of 163 analyzed sectors.

Overall, synergies are observed in mining and chemical fertilizer production (see Synergies quadrant in Figure 5). This occurs because the model allocates a reduction in chemical fertilizer use for both regions, leading to lower final demand for mining activities associated with fertilizer production and, consequently, a decrease in GHG emissions footprints in both LAC and the EU final demands. In contrast, losses are found in waste treatment sectors and organic composting activities, driven by increased demand for organic compost in the LAC agricultural sector (see Losses quadrant in Figure 5). While organic composting reduces reliance on chemical fertilizers, it can also lead to higher process-related emissions, particularly from biological decomposition and energy-intensive waste management operations.

Trade-offs in GHG emissions footprints for the EU and LAC final demands are observed across other sectors, including agriculture, food manufacturing, construction, and services (see Trade-offs quadrant in Figure 5). These trade-offs are relatively marginal, with a general 'win' situation for LAC (lower GHG emissions footprint) and a 'lose' situation for the EU (higher GHG emissions footprint). This pattern is mostly attributed to changes in trade flows between the two regions, where LAC benefits from shifting towards CE strategies, while the EU final demand experiences an increase in imported embodied emissions from LAC's agricultural and food processing sector.

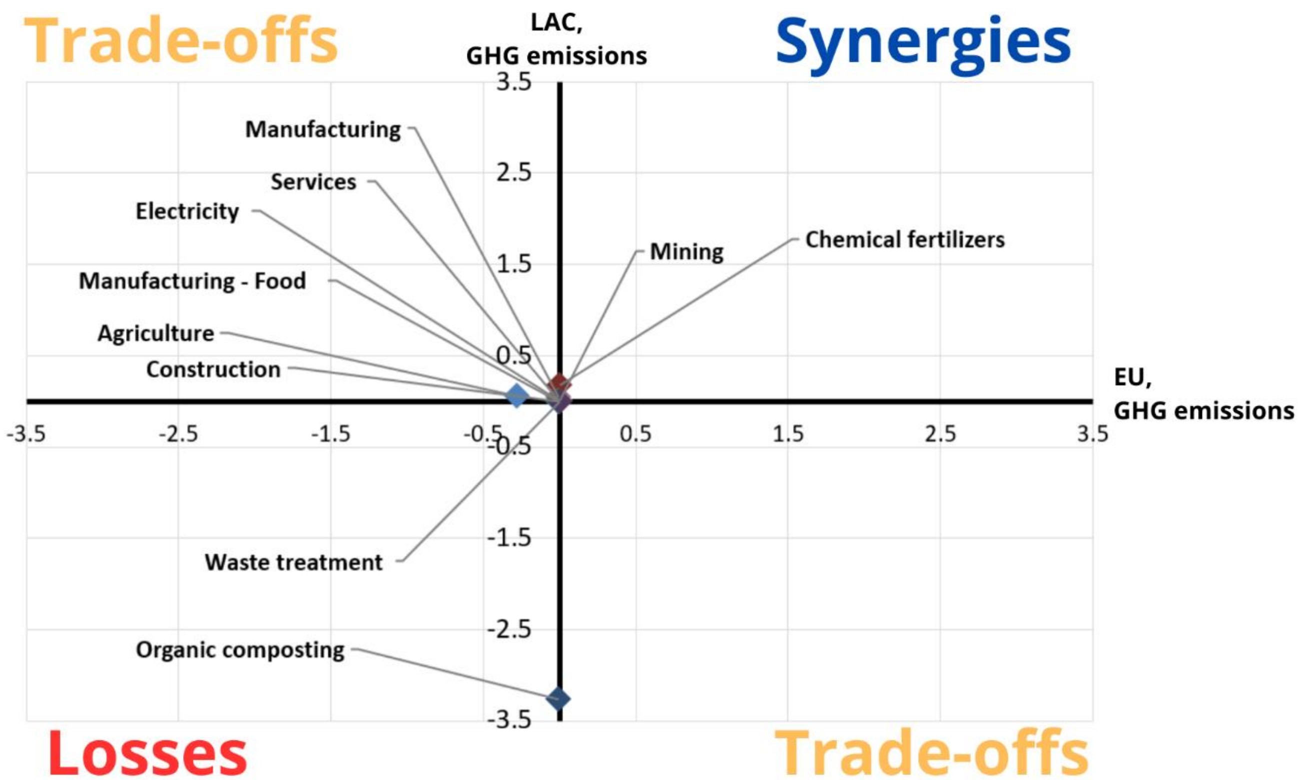

Figure 5. Circularity Trade-Offs, Synergies, and Losses of the EU and LAC Circularity Interventions in the Construction Sector Across 10 Aggregated Sectors for GHG Emissions

To synthesize the information, Figure 6 illustrates the share of trade-offs, synergies, and losses between the EU and LAC resulting from implementing the selected CE interventions. Following Step 4 - Trade-off and Synergies Analysis, the results are estimated by the Euclidean sum in Equation [5].

For value added, the results indicate 44% trade-offs, 36% synergies, and 20% losses. Synergies are driven by increases in value added in waste treatment and organic composting activities, reflecting the economic benefits of expanding circular processes. Trade-offs occur due to increased value added in agriculture from the EU final demand, while experiencing an overall reduction in agricultural value added from LAC final demand. Losses are linked to reduced value added in chemical fertilizer production, as demand for this activity declines under the proposed CE scenario.

Employment shows 82% trade-offs, 16% synergies, and 2% losses. This shift is largely due to changes in labor intensity across sectors and regions. Trade-offs emerge as EU final demand leads to increasing embodied employment across the regions, while LAC final demand drives a reduction in embodied employment, reflecting the regional redistribution of labor demand. The service sector also plays a role in trade-offs, as EU consumption leads to higher employment in services, while LAC experiences a decline. Synergies are observed in waste treatment and organic composting. Meanwhile, employment losses are concentrated in chemical fertilizer production, following the same pattern as value added synergies and losses.

For GHG emissions, the results indicate 86% losses, 10% trade-offs, and 4% synergies. The main contributors to losses are organic composting and waste treatment. However, as previously discussed, these results should be interpreted with caution, as the scenario analysis does not account for feedback loops or the broader carbon cycle, which could offset some of the reported emissions. Synergies are associated with reductions in chemical fertilizer use due the EU and LAC final demand reductions. It is important to note that these outcomes are directly influenced by the modeling assumptions outlined in Section 2.3.1, reinforcing that this is a hypothetical scenario designed to demonstrate the framework's application.

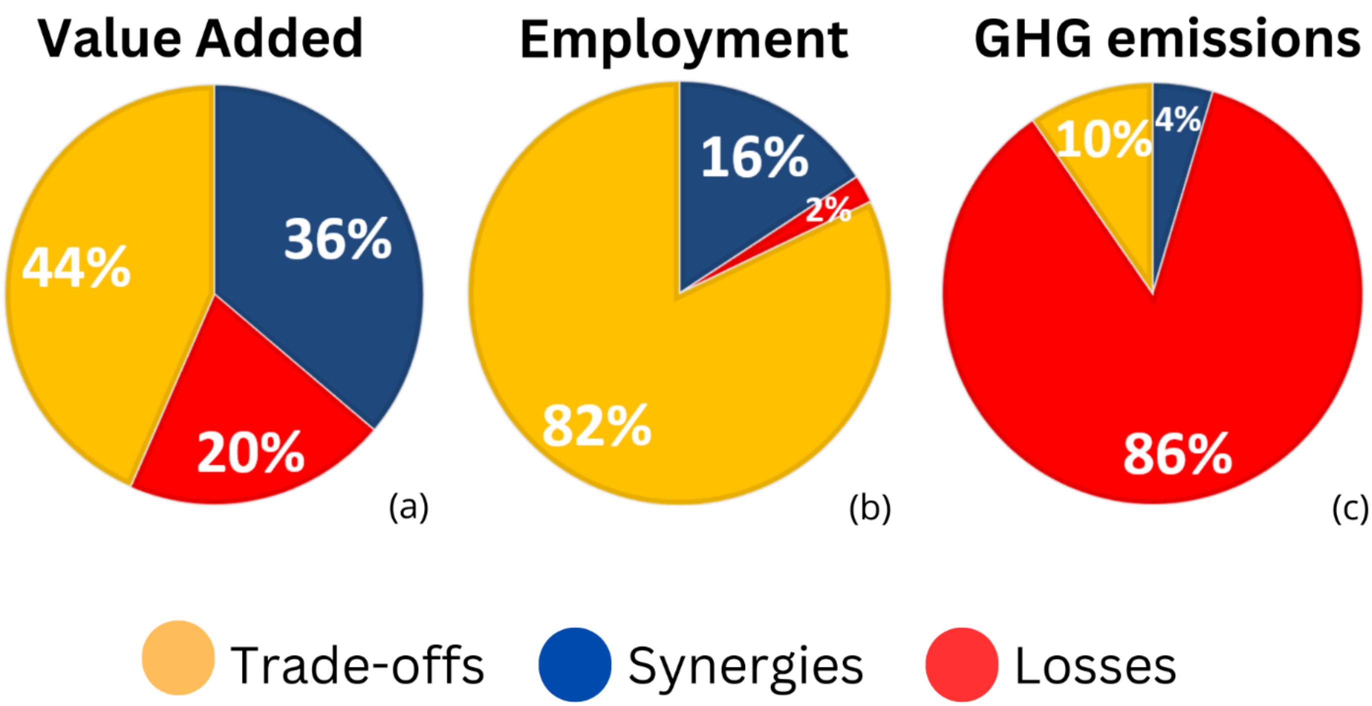

Figure 6. Share of Trade-Offs, Synergies, Losses, and Ties Between the EU and LAC Circularity Interventions in the Construction Sector for (a) Value Added, (b) Employment, and (c) Global Warming Potential

Overall, the granularity provided by the framework allows us to revisit the concatenation phase to pinpoint specific sectors experiencing gains or losses from the CES. This level of detail is crucial for two main reasons. First, it provides targeted policy interventions that contribute to understanding which sectors benefit and which face challenges, enabling policymakers to design targeted support mechanisms (e.g., incentives for industries experiencing losses or reinvestment strategies for displaced workers). Second, the level of granularity brings opportunities for an effective trade-off management. Measuring sector-specific trade-offs and synergies ensures that CE policies do not unintentionally disrupt economic stability in vulnerable sectors while maximizing CE benefits across regions and industries. For instance, if the chemical fertilizer sector experiences a decline in value added and employment, policymakers could mitigate negative impacts by facilitating workforce transitions to growing CE-related industries. Likewise, recognizing synergies in waste treatment and organic composting could justify investments in waste infrastructure, thereby amplifying positive economic and environmental impacts.

Comprising the trade-offs and synergies analysis into easy-to-read figures—such as Figure 6—enhances the communication of results, making them more accessible and actionable for policymakers. Well-structured visualizations serve three key functions:

1. Simplifying complexity: Translating multi-dimensional data into a clear, visual format allows decision-makers to quickly grasp the overall 'winners' and 'losers' of CE scenarios.
2. Guiding policy priorities: By visually highlighting sectors experiencing synergies, trade-offs, or losses, policymakers can identify critical areas for intervention and prioritize actions accordingly.
3. Supporting evidence-based decisions: When policymakers are presented with clear, data-driven insights, they can justify strategic policy adjustments based on sector-specific challenges and opportunities.

For instance, if the trade-offs and synergies analysis demonstrates that employment in waste treatment and composting increases while chemical fertilizer jobs decline, a hypothetical policy response could be redirecting subsidies from synthetic fertilizers to organic alternatives, ensuring that affected workers are transitioned into emerging CE sectors. Similarly, if trade-offs indicate increased embodied GHG emissions in certain sectors, this could prompt additional carbon mitigation strategies to balance environmental and economic trade-offs.

A pivotal aspect of the framework is that it enables the extraction of detailed information for scientific and/or technical purposes (e.g., as in Donati et al., 2020; Wiebe et al., 2019), alongside a unified version containing all relevant information that remains accessible for policymakers. The development of visual tools to facilitate communication between science and policy is not a novel concept, but in this context, the framework offers a structured, step-by-step approach tailored to CE scenario modeling. Here, the framework functions like an 'accordion'— capable of expanding or contracting to provide the appropriate level of detail—much like adjusting the 'notes' to fit the audience. This adaptability ensures that the framework can be used to transition between granular analysis and synthesized information, maintaining consistency across all elements.

The hypothetical scenario of potential trade-offs and synergies between the EU and LAC regions serves as an instructive example of how the proposed framework can be applied. Within the CE literature, the significance of understanding CE implications across multiple regions is well recognized, and the gap in identifying potential winners and losers, particularly in the Global North-South interactions (Aguilar-Hernandez et al., 2021; OECD, 2022). Although the example in this paper explores only a limited number of CE strategies, it provides sufficient complexity to demonstrate the framework's applicability. Moreover, including an Open-access code establishes a robust foundation for applying and enhancing the framework to other CES and modeling approaches. The following section elaborates on how this framework can be further improved.

3.2 Further Development

While the current framework effectively measures trade-offs and synergies, it does not assess the optimal set of CE interventions that maximize synergies while minimizing trade-offs and losses. To address this limitation, a potential extension could involve integrating a DEA module into the Python code, incorporating linear programming to resolve an optimization problem (e.g., in Bronner et al., 2022; Ezici et al., 2020). This enhancement would allow for the identification of the most effective CE strategies tailored to specific contexts. Furthermore, incorporating stakeholders' perspectives into the CES setting is crucial to ensuring the robustness and relevance of the framework's assumptions. By integrating MCDA principles into Steps 1 – Scenario Analysis and 2 – Data Harmonization, policymakers' insights can be incorporated into scenario development and data processes, enhancing the framework's reliability and utility.

Dynamic aspects are also important considerations in the assessment of circularity implications. While the current framework does not address a temporal dimension, future iterations could integrate dynamic models such as applying the framework to outcomes from dynamic Material Flow Analysis (for example, Pauliuk et al., 2017; Vélez-Henao & Pauliuk, 2025; Wiedenhofer et al., 2019). This would enable the identification of temporal changes in trade-offs and synergies, providing valuable insights for long-term planning and decision-making.

4. FINAL REMARKS

This paper introduces a novel framework to measure potential trade-offs and synergies between Circular Economy scenarios. By adopting a multi-dimensional approach, this framework offers a comprehensive overview of the implications of CE strategies, thereby facilitating policymakers' understanding of the potential benefits and costs associated with the CE implementation. Drawing upon principles from Multi-Criteria Decision Analysis, Triple-Bottom-Line, and Data Envelopment Analysis, the framework provides a systematic approach for exploring the 'winners' and 'losers' in a circularity transition.

Beyond the technical advancements introduced in this framework, a key contribution of this work lies in its ability to enhance communication of circularity trade-offs and synergies to key stakeholders, especially policymakers. A central feature is its capability to condense results from complex scenario analyses into accessible, easy-to-read visualizations tailored to the audience's needs. This aspect is specifically designed to support policymakers in interpreting and utilizing the findings from CES modelling effectively. Furthermore, future developments emphasize the potential for enhancing stakeholder participation in CES development and data harmonization processes, bringing a co-creation approach that benefits both CE researchers and policymakers in exploring the potential implications of a CE transition.

By providing a step-wise process (including a Python code that facilitates the use of the framework), this work encourages researchers and practitioners to collaborate and improve the quantification of circularity impacts. Looking ahead, continued efforts to refine and expand this framework will be essential for navigating the complexities of circularity transitions and ensuring their effectiveness and fairness on a global scale.

ACKNOWLEDGEMENTS

I would like to thank the participants of the Special Session on Advances in Circular Economy Modelling at the 30th International Input-Output Association Conference for their valuable insights. Furthermore, I would like to thank two anonymous reviewers that have contributed to improving the quality of this manuscript.
During the preparation of this manuscript, I used an AI tool in order to improve the readability and language. After using this tool, I reviewed and edited the content as needed and take full responsibility for the content of the publication.

The journal thanks Sydney P. Bazilian for their administrative assistance throughout the publication process.

AUTHOR CONTRIBUTIONS

Glenn A. Aguilar-Hernandez: Sole author.

DECLARATIONS

Competing interests The author declare no competing interests.
Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.
Funding Glenn A. Aguilar-Hernandez is a Research Fellow of the UNravelling the socioeconomic and environmental Impacts of Circularity in Latin America (UNICA) project, which is funded by European Commission under Marie Skłodowska-Curie Actions (Grant Agreement: 101103532).

SUPPLEMENTARY INFORMATION

Supplementary information, including scenario analysis, results and Python code, is available at the DOI 10.5281/zenodo.15223878

REFERENCES

Aguilar-Hernandez, G. A. (2024). A MR EEIO-based framework for identifying synergies and trade-offs of circularity interventions. Paper presented at the 30th International Input-Output Association Conference, Santiago, Chile. In *Paper presented at the 30th International Input-Output Association Conference, Santiago, Chile*. https://www.iioa.org/conferences/30th/papers.html

Aguilar-Hernandez, G. A., Dias Rodrigues, J. F., & Tukker, A. (2021). Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. *Journal of Cleaner Production*, *278*. https://doi.org/10.1016/j.jclepro.2020.123421

Aguilar-Hernandez, G. A., Hoof, B. Van, Conde, Á., Kahhat, R., & Pabón-Pereira, C. (2024). Enabling Mechanisms for Circularity in Latin America and the Caribbean. *Journal of Circular Economy*, *2*(3). https://doi.org/10.55845/IKHI7118

Belton, V., & Stewart, T. J. (2002). Multiple Criteria Decision Analysis. In *Multiple Criteria Decision Analysis*. Springer US. https://doi.org/10.1007/978-1-4615-1495-4

Bibas, R. , Chateau, J., & Lanzi, E. (2021). *Policy scenarios for a transition to a more resource efficient and circular economy*.

Bronner, M., See, K. F., & Yu, M. M. (2022). Circular water economy performance evaluation based on dynamic network data envelopment analysis. *Journal of Cleaner Production*, *367*. https://doi.org/10.1016/j.jclepro.2022.132474

Çetinay, H., Donati, F., Heijungs, R., & Sprecher, B. (2020). Efficient computation of environmentally extended input–output scenario and circular economy modeling. *Journal of Industrial Ecology*, *24*(5), 976–985. https://doi.org/10.1111/jiec.13013

Chateau, J., & Mavroeidi, E. (2020). *The jobs potential of a transition towards a resource efficient and circular economy*.

Cinelli, M., Kadziński, M., Gonzalez, M., & Słowiński, R. (2020). How to support the application of multiple criteria decision analysis? Let us start with a comprehensive taxonomy. In *Omega (United Kingdom)* (Vol. 96). Elsevier Ltd. https://doi.org/10.1016/j.omega.2020.102261

Cinelli, M., Kadziński, M., Miebs, G., Gonzalez, M., & Słowiński, R. (2022). Recommending multiple criteria decision analysis methods with a new taxonomy-based decision support system. *European Journal of Operational Research*, *302*(2), 633–651. https://doi.org/10.1016/j.ejor.2022.01.011

Circle Economy. (2023). *The Circularity Gap Report - Latin America and the Caribbean*. https://www.circularity-gap.world/lac

Coalition of Circular Economy from Latin America & Caribbean. (2022). *Circular Economy in Latin America and the Caribbean: A Shared Vision*. https://coalicioneconomiacircular.org/en/economia-circular-en-america-latina-y-el-caribe-una-vision-compartida/

Cook, W. D., & Seiford, L. M. (2009). Data envelopment analysis (DEA) - Thirty years on. *European Journal of Operational Research*, *192*(1), 1–17. https://doi.org/10.1016/j.ejor.2008.01.032

Costa, B. V. de L., Cordeiro, N. G., Bocardi, V. B., Fernandes, G. R., Pereira, S. C. L., Claro, R. M., & Duarte, C. K. (2024). Food loss and food waste research in Latin America: scoping review. In

Ciencia & saude coletiva (Vol. 29, Issue 10, p. e04532023). https://doi.org/10.1590/1413-812320242910.04532023

Della Bella, S., Sen, B., Cimpan, C., Rocco, M. V., & Liu, G. (2023). Exploring the Impact of Recycling on Demand-Supply Balance of Critical Materials in Green Transition: A Dynamic Multi-Regional Waste Input-Output Analysis. *Environmental Science and Technology*, *57*(28), 10221–10230. https://doi.org/10.1021/acs.est.2c09676

Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*(November 2018). https://doi.org/10.1016/j.resconrec.2019.104508

Ezici, B., Eğilmez, G., & Gedik, R. (2020). Assessing the eco-efficiency of U.S. manufacturing industries with a focus on renewable vs. non-renewable energy use: An integrated time series MRIO and DEA approach. *Journal of Cleaner Production*, *253*, 119630. https://doi.org/10.1016/j.jclepro.2019.119630

Fan, Y., & Fang, C. (2020). Circular economy development in China-current situation, evaluation and policy implications. *Environmental Impact Assessment Review*, *84*. https://doi.org/10.1016/j.eiar.2020.106441

FAO. (2014). *Food Losses and Waste in Latin America and the Caribbean*. https://openknowledge.fao.org/server/api/core/bitstreams/99a55774-bff0-4a2a-83f3-a4ff2b345ede/content

Gallego-Schmid, A., López-Eccher, C., Muñoz, E., Salvador, R., Cano-Londoño, N. A., Barros, M. V., Bernal, D. C., Mendoza, J. M. F., Nadal, A., & Guerrero, A. B. (2024). Circular economy in Latin America and the Caribbean: Drivers, opportunities, barriers and strategies. In *Sustainable Production and Consumption* (Vol. 51, pp. 118–136). Elsevier B.V. https://doi.org/10.1016/j.spc.2024.09.006

Haase, D., Schwarz, N., Strohbach, M., Kroll, F., & Seppelt, R. (2012). Synergies, Trade-offs, and Losses of Ecosystem Services in Urban Regions: an Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany. *Ecology and Society*, *17*(3), art22. https://doi.org/10.5751/ES-04853-170322

Hacking, T., & Guthrie, P. (2008). A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. *Environmental Impact Assessment Review*, *28*(2–3), 73–89. https://doi.org/10.1016/j.eiar.2007.03.002

He, Z., Ding, B., Pei, S., Cao, H., Liang, J., & Li, Z. (2023). The impact of organic fertilizer replacement on greenhouse gas emissions and its influencing factors. In *Science of the Total Environment* (Vol. 905). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2023.166917

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. In *Science of the Total Environment* (Vol. 409, Issue 19, pp. 3578–3594). https://doi.org/10.1016/j.scitotenv.2011.06.022

Luthin, A., Crawford, R. H., & Traverso, M. (2024). Assessing the circularity and sustainability of circular carpets — a demonstration of circular life cycle sustainability assessment. *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-024-02359-x

Mardani, A., Zavadskas, E. K., Streimikiene, D., Jusoh, A., & Khoshnoudi, M. (2017). A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. In

Renewable and Sustainable Energy Reviews (Vol. 70, pp. 1298–1322). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.12.030

McCarthy, A., Dellink, R., & Bibas, R. (2018). *The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches*.

Mcwilliams, A., Parhankangas, A., Coupet, J., Welch, E., & Barnum, D. T. (2016). Strategic Decision Making for the Triple Bottom Line. *Business Strategy and the Environment*, *25*(3), 193–204. https://doi.org/10.1002/bse.1867

Merli, R., Preziosi, M., & Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *Journal of Cleaner Production*, *178*, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112

Miller, R. E., & Blair, P. D. (2009). *Input–Output Analysis: Foundations and Extensions* (Second edi). Cambridge University Press.

MinAmbiente. (2019). *Estrategia Nacional de Economía Circular - Colombia*. https://archivo.minambiente.gov.co/index.php/estrategia-nacional-de-economia-circular-ec

Minx, J. C., Lamb, W. F., Andrew, R. M., Canadell, J. G., Crippa, M., Döbbeling, N., Forster, P., Guizzardi, D., Olivier, J., Pongratz, J., Reisinger, A., Rigby, M., Peters, G., Saunois, M., Smith, S. J., Solazzo, E., & Tian, H. (2022). *A comprehensive and synthetic dataset for global, regional and national greenhouse gas emissions by sector 1970-2018 with an extension to 2019*. https://doi.org/10.5281/zenodo.5053055.

MMA. (2020). *Hoja de Ruta para un Chile Circular al 2040*. https://economiacircular.mma.gob.cl/hoja-de-ruta/

Mohsin, A. K. M., Gerschberger, M., Plasch, M., Ahmed, S. F., Rahman, A., & Rashed, M. (2024). Examining the synergy of green supply chain practices, circular economy, and economic growth in mitigating carbon emissions: Evidence from EU countries. *Journal of Environmental Management*, *371*. https://doi.org/10.1016/j.jenvman.2024.123109

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., & Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, *146*, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045

OECD. (2022). *Synergies and trade-offs in the transition to a Resource-Efficient and Circular Economy POLICY PERSPECTIVES*.

Onat, N. C., Kucukvar, M., & Tatari, O. (2014). Integrating triple bottom line input-output analysis into life cycle sustainability assessment framework: The case for US buildings. *International Journal of Life Cycle Assessment*, *19*(8), 1488–1505. https://doi.org/10.1007/s11367-014-0753-y

Padilla-Rivera, A., do Carmo, B. B. T., Arcese, G., & Merveille, N. (2021). Social circular economy indicators: Selection through fuzzy delphi method. *Sustainable Production and Consumption*, *26*, 101–110. https://doi.org/10.1016/j.spc.2020.09.015

Pauliuk, S., Kondo, Y., Nakamura, S., & Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. *Resources, Conservation and Recycling*, *116*, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029

Quintelier, K. J. P., van Bommel, K., van Erkelens, A. M., & Wempe, J. (2023). People at the heart of circularity: A mixed methods study about trade-offs, synergies, and strategies related to circular and social organizing. *Journal of Cleaner Production*, *387*. https://doi.org/10.1016/j.jclepro.2022.135780

Repp, L., Hekkert, M., & Kirchherr, J. (2021). Circular economy-induced global employment shifts in apparel value chains: Job reduction in apparel production activities, job growth in reuse and recycling activities. *Resources, Conservation and Recycling*, *171*. https://doi.org/10.1016/j.resconrec.2021.105621

Rietveld, E., Bastein, T., Boonman, H., Melo, L., Hauck, M., Donati, F., Merciai, S., Deetman, S., & Aguilar-Hernandez, G. A. (2021). *Learning from circular economy relevant modelling approaches. TNO Report*. https://publications.tno.nl/publication/34639393/iNBntE/TNO-2021-R12237.pdf

Romero, C. A., Rojo Brizuela, S., & Ferro, G. (2024). Measuring the Effects of Increasing Circularity in the Economy Through Recycling. In *Circular Economy and Sustainability* (Vol. 4, Issue 1, pp. 503–522). Springer Nature. https://doi.org/10.1007/s43615-023-00299-6

Ross, A. G., Connolly, K., Rhoden, I., & Vögele, S. (2023). Resource-use intensity and the labour market: More for less? *Environmental Impact Assessment Review*, *102*. https://doi.org/10.1016/j.eiar.2023.107173

Safarzynska, K., Di Domenico, L., & Raberto, M. (2023). The leakage effect may undermine the circular economy efforts. *Scientific Reports*, *13*(1), 1–15. https://doi.org/10.1038/s41598-023-44004-x

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, *119*, 314–325. https://doi.org/10.1016/j.ecolecon.2015.09.015

Samaniego, J., Rondón Toro, E., Herrera Jiménez, J., & Santori, S. (2022). *Panorama de las hojas de ruta de economía circular en América Latina y el Caribe. Documentos de Proyectos*. https://www.cepal.org/es/publicaciones/48632-panorama-hojas-ruta-economia-circular-america-latina-caribe

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019

Sasso, R. A., Filho, M. G., & Ganga, G. M. D. (2024). Synergizing lean management and circular economy: Pathways to sustainable manufacturing. *Corporate Social Responsibility and Environmental Management*. https://doi.org/10.1002/csr.2962

Scherer, L., Behrens, P., de Koning, A., Heijungs, R., Sprecher, B., & Tukker, A. (2018). Trade-offs between social and environmental Sustainable Development Goals. *Environmental Science and Policy*, *90*, 65–72. https://doi.org/10.1016/j.envsci.2018.10.002

Schroeder, P., Dewick, P., Kusi-Sarpong, S., & Hofstetter, J. S. (2018). Circular economy and power relations in global value chains: Tensions and trade-offs for lower income countries. In *Resources, Conservation and Recycling* (Vol. 136, pp. 77–78). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2018.04.003

Tahavori, M. A., Golinucci, N., Rinaldi, L., Rocco, M. V., & Colombo, E. (2023). MARIO: A Versatile and User-Friendly Software for Building Input-Output Models. *Journal of Open Research Software*, *11*. https://doi.org/10.5334/jors.473

Towa, E., Zeller, V., & Achten, W. M. J. (2021). Circular economy scenario modelling using a multiregional hybrid input-output model: The case of Belgium and its regions. *Sustainable Production and Consumption*, *27*, 889–904. https://doi.org/10.1016/j.spc.2021.02.012

UNEP. (2024). *Global Resource Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes*. https://doi.org/https://wedocs.unep.org/20.500.11822/44901

Vanclay, F. (2004). THE TRIPLE BOTTOM LINE AND IMPACT ASSESSMENT: HOW DO TBL, EIA, SIA, SEA AND EMS RELATE TO EACH OTHER? In *JEAPM Journal of Environmental Assessment Policy and Management* (Vol. 6, Issue 3). www.worldscientific.com

Veiga, J. P. S., Malik, A., Lenzen, M., Ferreira Filho, J. B. de S., & Romanelli, T. L. (2018). Triple-bottom-line assessment of São Paulo state's sugarcane production based on a Brazilian multi-regional input-output matrix. In *Renewable and Sustainable Energy Reviews* (Vol. 82, pp. 666–680). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.09.075

Vélez-Henao, J. A., & Pauliuk, S. (2025). Pathways to a net zero building sector in Colombia: Insights from a circular economy perspective. *Resources, Conservation and Recycling*, *212*. https://doi.org/10.1016/j.resconrec.2024.107971

Verma, N., Talwar, P., Upadhyay, A., Singh, R., Lindenberger, C., Pareek, N., Sarangi, P. K., Zorpas, A. A., & Vivekanand, V. (2024). Food-Energy-Water Nexus in compliance with Sustainable Development Goals for integrating and managing the core environmental verticals for sustainable energy and circular economy. *Science of the Total Environment*, *930*. https://doi.org/10.1016/j.scitotenv.2024.172649

Wang, S., Lei, L., & Xing, L. (2021). Urban circular economy performance evaluation: A novel fully fuzzy data envelopment analysis with large datasets. *Journal of Cleaner Production*, *324*. https://doi.org/10.1016/j.jclepro.2021.129214

Wiebe, K. S., Harsdorff, M., Montt, G., Simas, M. S., & Wood, R. (2019). Global Circular Economy Scenario in a Multiregional Input-Output Framework. *Environmetal Science & Technology*, *56*(11), 6362–6373. https://doi.org/10.1021/acs.est.9b01208

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting : Concepts , Modelling , and Global Application for 1900 – 2050. *Ecological Economics*, *156*, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis. *Ecological Economics*, *70*(11), 1937–1945. https://doi.org/10.1016/j.ecolecon.2011.06.014

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., & Tukker, A. (2015). Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, *7*(1), 138–163. https://doi.org/10.3390/su7010138