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Title: A MR EEIO-based framework for identifying synergies and trade-offs of circularity interventions

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Abstract

In recent years, there has been an increase of studies exploring the potential socioeconomic and environmental impacts of a circular economy at country and regional level. However, understanding the potential trade-offs and synergies of circularity interventions remains limited. This paper presents a novel framework for identifying circularity trade-offs and synergies using a multi-regional environmentally extended input-output (MR EEIO) approach. By considering three key dimensions (impact, geographical, and sectoral), this framework offers a step-wise process for analyzing circularity trade-offs and synergies in a multi-dimensional and systematic manner. To demonstrate the application of the MR EEIO-based framework, a case study is conducted to identify key trade-offs and synergies of implementing circularity interventions in both the European Union and Latin American construction sector. This work contributes to a better understanding of the winners and losers of a global circularity transition, and facilitates the communication of circular economy scenarios to policymakers.

1. Introduction

Circular economy scenarios (CES) have contributed to understanding the potential economic, social, and environmental implications of a circularity transition on a country and global scale using macroeconomic models[1]. Several researchers have identified potential trade-offs within circularity interventions[2–4]. 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 Lantin America). Although several CES point out 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 them systematically.

Several frameworks have been developed to identify trade-offs and synergies. For example, the application of multi-criteria decision, data envelop analysis, and triple-bottom line approaches has facilitated the identification of trade-offs between socio-economic and environmental impacts of multiple interventions[5–7]. 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[8]. With modern applications, MCDA has evolved since its beginnings, and played a prominent role in decision-making processes, including in policy-related questions[9]. As a systematic framework, MCDA involves three core components: identifying alternatives, establishing criteria, and generating recommendations[9]. A notable feature of MCDA is its interactive nature, involving stakeholders throughout the development process, which enables a more robust decision-making environment.

Triple-bottom-line (TBL) considers three fundamental dimensions of sustainability: economy, society, and environment[7]. 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[10]. From a consumption-based perspective, several studies have applied TBL principles, employing environmentally-extended input-output analysis (EEIOA) to assess socio-economic and environmental performances of different economies[11–13]. 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 circular economy strategies across diverse value chains (e.g., textile, plastics, construction) in the Norwegian economy, utilizing a dynamic multi-regional EEIO (MR EEIO) model[14].

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[15]. Similar to cost-benefit analysis, DEA distinguishes between positive and negative parameters of decision-making processes, facilitating the identification of potential trade-offs within operations[10,16]. DEA operates as an optimization technique, typically involving linear programming to either maximize or minimize certain systems. DEA has been applied across various levels, from analyzing business strategies to nation-wide assessments[17–19]. Its key aspect lies in the formulation of decision-making units (DMUs), which are utilized to solve an optimization problems[19]. Thus, DMUs are key units to determine whether alternatives offer potential positive or negative impacts on a system.

Within this context, multiple approaches have been used as a quantitative tool for exploring potential trade-offs and synergies[20,21]. However, to the best of my knowledge, there is no systematic way to identify and assess trade-offs and synergies of circularity interventions, especially considering potential direct and indirect impacts between the Global North and South circularity transitions. This raises the question: “How can the potential trade-offs and synergies of different circularity interventions be systematically identified to facilitate the interpretation of CES modeling in MR EEIO?”

In this paper, I aim to develop a novel MR EEIO-based framework for identifying trade-offs and synergies of circularity interventions. 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 MR EEIOA-based framework that allows for the identification and assessment of trade-offs and synergies of multiple circularity interventions in a systematic way. This work contributes to facilitating the interpretation of CES modeling and support decision-making in CE policies.

2. Method

Firstly, I defined the key dimensions of circularity trade-offs and synergies through a literature review. Then, I created a step-wise framework, including algebraic expressions to identify trade-offs and synergies in an MR EEIO system. Lastly, I developed a Python code, and illustrated the use of the MR EEIO framework with a case study focusing on the potential trade-offs and synergies between the European Union (EU) and Latin America (LATAM) if both regions implement circularity interventions simultaneously.

2.1. Data and scenario analysis

To illustrate the application of the MR EEIO-based framework, I conducted a geographical trade-offs and synergies analysis focusing on the EU and LATAM regions. For this example, I applied the MR EEIOA model developed by Donati et al.[22], using the IOT industry-by-industry for 2019 from EXIOBASE v3.8.2 (available at: https://zenodo.org/record/5589597). The proposed framework was implemented, incorporating the key dimensions—geographical, impact, and sectoral. EU member countries were aggregated into a single EU region, while LATAM encompassed Mexico, Brazil, and the remainder of Latin America and the Caribbean, following EXIOBASE country/region classification (further details provided in Supplementary Material).

The impacts of circularity interventions in the construction sector are analyzed if both regions implement circularity interventions simultaneously. The impact dimensions considered are changes in value added, employment, and global warming potential (GWP-100) for 2019. For modelling, I applied the circular economy scenarios (CES) brought by Donati et al.[22]. Table 1 summarizes the assumptions for the CES in the EU and LATAM construction sector.

Table 1. Circular economy scenario assumptions for interventions in the EU and LATAM construction sector. Based on Donati et al.[22]

CE strategies	Interventions applied to MR EEIO
Product lifetime extension	Increasing refurbishment by 40% in the EU and LATAM
	Increasing 60% inter-industry demand of construction-construction in EU and LATAM
	Decreasing 60% of construction from the EU and LATAM final demand
Resource efficiency	Replacing 90% of primary steel with secondary steel in the EU and LATAM construction sector
	Replacing 90% of primary aluminum with secondary steel in the EU and LATAM construction sector
	Increasing 50% occupancy of non-residential buildings in the EU and LATAM

Further details, including scenario analysis, results and Python code, are available on: https://github.com/aguilarga/circularity_trade-offs-synergies_supplementary_material

3. Circularity trade-offs and synergies

In the context of CE policies, trade-offs and synergies play crucial roles in 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 a 'win-lose' situation, whereas synergies arise when circularity interventions have positive effects on multiple parts of a system, leading to a 'win-win' situation[23]. Likewise, losses occur when both part of a system are negatively impacted, having a ‘lose-lose’ situation.

Analyses of over 300 CES suggest that synergies are more prevalent within isolated countries, particularly in terms of changes in GDP, job creation, and GHG emissions[1]. However, considering broader systems shows potential for trade-offs across multiple-dimensions, requiring a structural assessment of circularity trade-offs and synergies[23,24]. Furthermore, it is essential to define the main dimensions for assessing circularity trade-offs and synergies. Here, three key dimensions emerge from previous CES: impacts, geographical, and sectoral dimensions (see figure 1).

The impacts dimension refers to the effects of circularity interventions across various impact indicators. For instance, CE implementation in the EU is projected to boost GDP by €900 billion and reduce GHG emissions by 50% by 2030, exemplifying a 'win-win' scenario[25]. This dimension is commonly assessed in Life Cycle Assessments (LCA) studies, primarily identifying trade-offs and synergies within economic and environmental indicators[26,27].

The geographical dimension focuses on the macro-level effects of CE implementation across multiple countries (or regions) within specific impact indicators. For example, assessing whether circularity interventions in the Global North would benefit both Northern and Southern regions in terms of economic growth illustrates the significance of this dimension. While this dimension remains relatively unexplored[1], integrated models like MR EEIO – as well as related CGEs, and Integrated Assessment models - facilitate the analysis of impacts across countries/regions[1,20,28]. For instance, for employment as a socioeconomic indicator, CES using MR EEIO models show that global adoption could increase employment within the EU by 2.7%, while in Asian economies, it might affect between -2.6% and 4.3%, bringing both 'win-win' and 'win-lose' situations across regions[4].

Zooming into the value chain, the sectoral dimension provides insights into potential trade-offs and synergies across sectors where circularity interventions are implemented. For instance, secondary-based metal production, services, and the recycling sector are expected to experience strong job creation, while primary materials extraction and materials-intensive sectors could face job reductions[29,30].

In all three dimensions, it is important to consider both direct and indirect impacts of circularity interventions when identifying the ‘winners’ and ‘losers’ to determine whether a particular CE implementation could yield net benefits or not. This underscores the significance of employing an MR EEIO-based framework, as MR EEIOA allows for the quantification of embodied impacts across these dimensions[31]. By integrating MR EEIO analysis, researchers can comprehensively evaluate the ripple effects of CE strategies, facilitating the interpretation of their potential outcomes and informing decision-making processes.

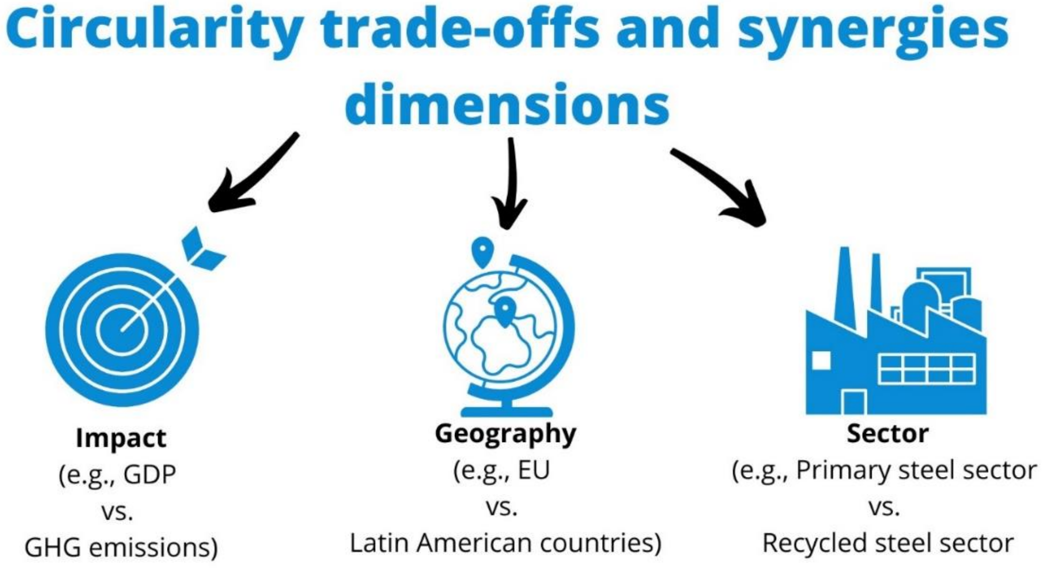

Figure 1. Key circularity trade-offs and synergies dimensions

4. MR EEIOA-based Trade-offs and Synergies framework

Considering the multi-dimensional aspects of circularity trade-offs and synergies, a novel MR EEIOA-based framework is proposed here as a structured approach to identify and assess the ‘winners’ and ‘losers’ of CE adoption. This framework, comprising four main steps, serves as a guideline for systematically evaluating circularity interventions.

- **Step 1: Scenario analysis**

By categorizing circularity interventions into distinct types - such as residual waste management, product lifetime extension, closing supply chains, and resource efficiency - CES can be modelled by using MR EEIOA[31]. CES represent the anticipated changes resulting from circularity interventions and can be compared against a business-as-usual (BAU) scenario to highlight structural changes. Mathematically, CES can be estimated as[32]:

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

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. 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. As explained by Donati et al.[22], modifying A implies structural changes which are core of circularity interventions, but it brings an unbalanced IO systems. This can be corrected by using balancing methods[4], or ignore if changes are considered marginal.

- **Step 2: Data harmonization**

Data harmonization involves normalizing CES impacts compared with 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 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 on the IO system.

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 for changes in GHG emissions would be 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 $N_i = 0$.

As in most of the cases environmental indicators are considered ‘wins’ if there is a reduction of environmental impacts in CES compared with BAU, it requires a sign harmonization when comparing economic and social indicators such as value added and job creation. Thus, signs should be change 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 notice that sign harmonization (as N_i^{SH}) requires the inclusion of stakeholders to decide which changes in impacts are considered a ‘win’ or ‘lose’ situation. In general, we would expected ‘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 MR EEIO-based framework.

- **Step 3: Concatenating dimensions**

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

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

Here, TS has m blocks of N_i^{SH} vectors concatenated horizontally. In a MR EEIO system, TS contains sectors s per country c in rows, and harmonized impacts i in columns, which means that each element of TS 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 TS matrix is structured within a cardinal system, enabling easy identification of trade-offs and synergies. 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 2). This interpretation follows the principles considered by several trade-offs and synergies studies (see, for example, Haase et al. [33]).

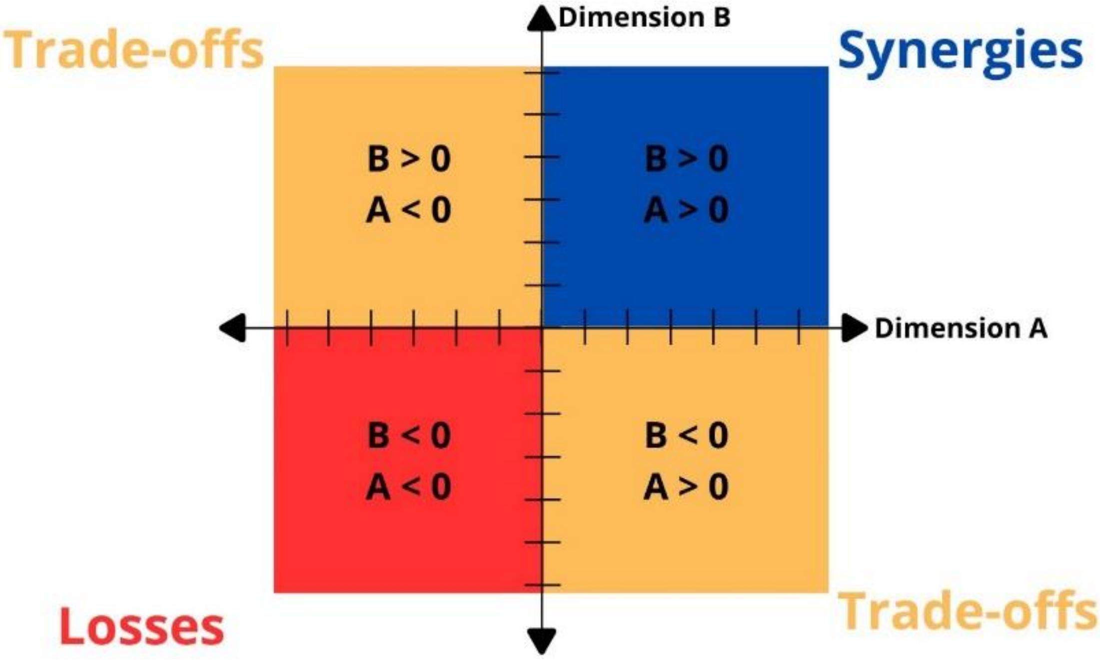

Figure 2. Diagram of trade-offs and synergies for two dimensions A and B. Synergies (in blue block) are 'win-win' situations, trade-offs (in yellow blocks) are 'win-lose' and 'lose-win', losses (in red block) are 'lose-lose' situations.

- **Step 4: Trade-offs and Synergies analysis**

Finally, the magnitude of trade-offs, synergies, and losses are quantified using an Euclidean approach. Similar to methods used for calculating DMUs in DEA studies, the overall magnitude of circularity trade-offs and synergies (v) is estimated by:

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

where ts_{dim-n} represents the elements of TS 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 $v_{A,B} = \sqrt{(ts_A)^2 + (ts_B)^2} = \sqrt{(-0.4)^2 + (0.5)^2} = 0.64$. Figure 3 shows a graphical representation of the trade-offs and synergies analysis.

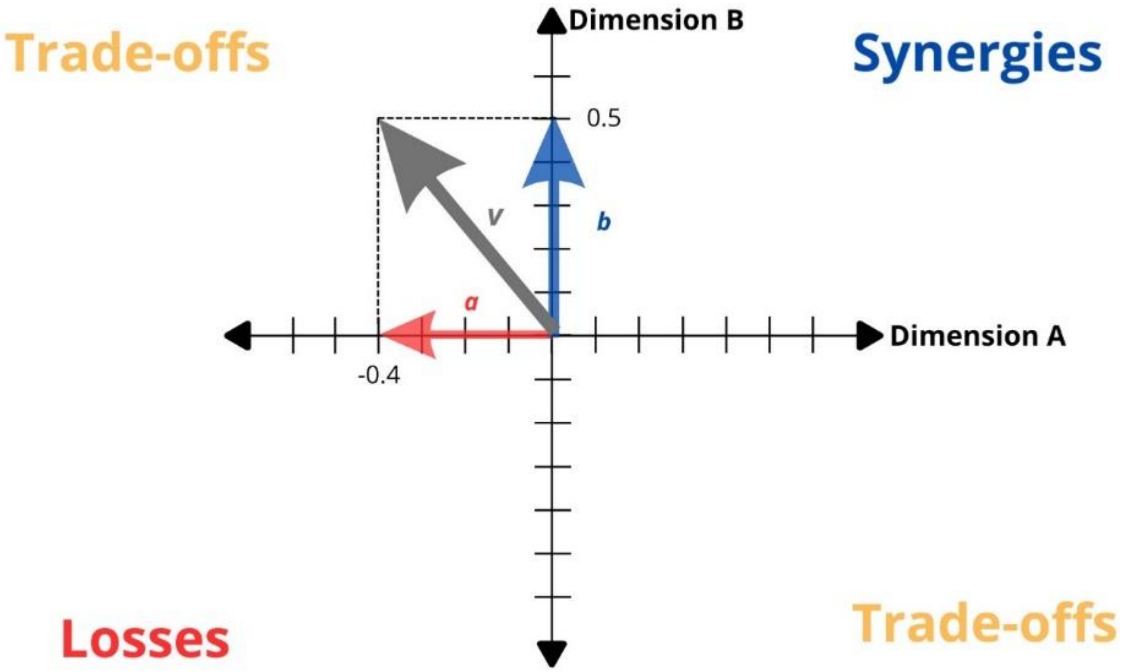

Figure 3. Example of magnitude of trade-offs and synergies for dimension A and B.

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_d represents each Euclidian vector for w number of data points.

5. Circularity Trade-offs and synergies between EU and LATAM

Figure 4 brings the aggregated results indicating changes in value added, employment, and global warming potential (GWP) resulting from the implementation of circularity interventions in both the EU and LATAM regions (using CES from table 1). In the EU, the overall changes observed from the CES compared with BAU scenarios indicates a reduction in value added and employment by -1.5% and -0.5%, respectively, while there is a decrease in GWP by -0.2% (adjusted to +0.2% following sign harmonization). Likewise, LATAM presented overall losses in value added and employment by -0.6%, combined with an increase in GWP by 0.2% compared with BAU scenario.

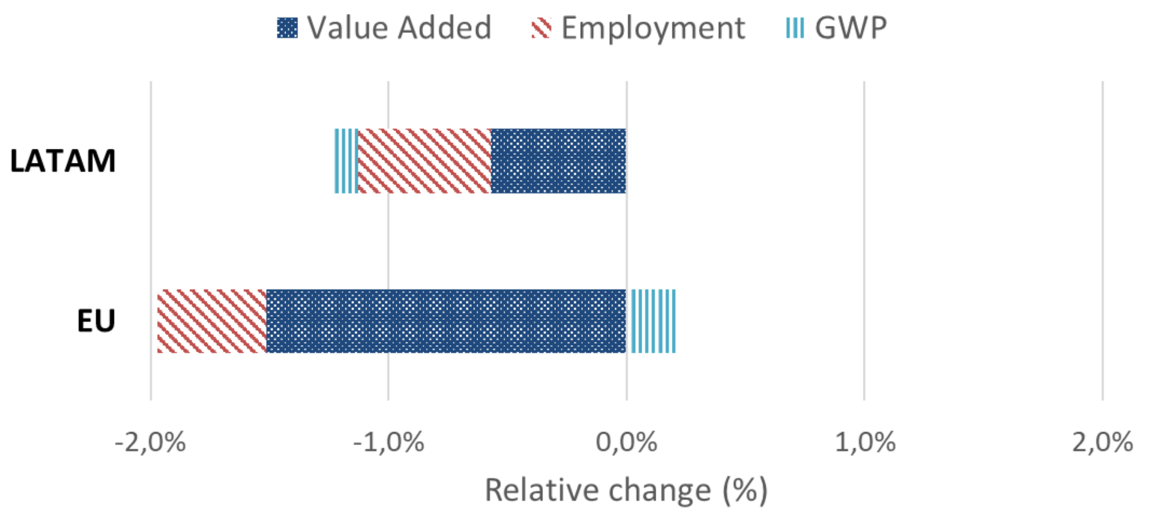

Figure 4. Relative changes in value added, employment, global warming potential (GWP) from the EU and LATAM circularity interventions in the construction sector.

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 GWP for LATAM and the EU, with each data point representing the changes in GWP per sector, encompassing a total of 163 sectors analyzed. Overall, main synergies are observed between the two regions in cement, lime, and plaster manufacturing, as well as in the construction sector itself. In contrast, losses are mainly found in the re-processing of secondary steel and aluminum sectors. Concatenating dimensions for value added and employment are available in the Supplementary Material (in ge_results.xlsx file).

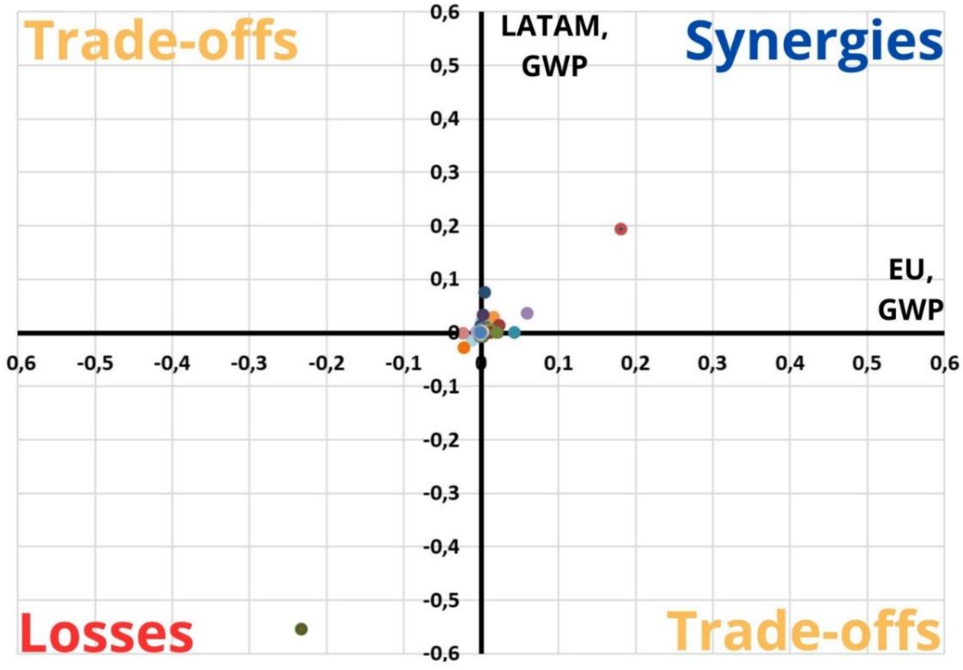

Figure 5. Circularity trade-offs, synergies, and losses of the EU and LATAM circularity interventions in the construction sector across all 163 sectors for global warming potential (GWP) impacts.

To synthesize the information, Figure 6 illustrates the share of trade-offs, synergies, and losses between the EU and LATAM resulting from implementing the selected circularity interventions. Following step 4, this representation is derived by computing the Euclidean sum in equation [5] per each category. Overall, this CES would generate losses for both regions concerning value added and employment, with respective shares of 90% and 94%. In contrast, GWP demonstrates a diverse array of outcomes, with 48% of synergies, followed by 45% losses, 4% trade-offs, and 3% tie situations. The granularity provided by the MR EEIO-based framework allows us to revisit the concatenation phase to pinpoint specific sectors experiencing gains or losses from the CES.

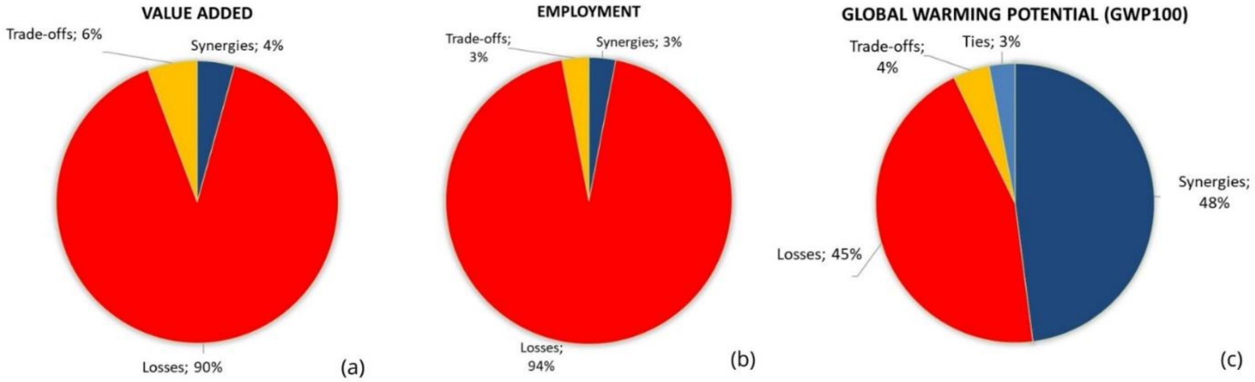

Figure 6. Share of trade-offs, synergies, losses, and ties between the EU and LATAM circularity interventions in the construction sector for (a) value added, (b) employment, and (c) global warming potential (GWP).

6. Discussion and final remarks

This paper introduces a novel MR EEIO-based framework to identify potential trade-offs and synergies from circularity interventions. 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 such interventions. Drawing upon principles from MCDA, TBL, and DEA, this framework provides a systematic method for exploring the winners and losers in a circularity transition.

While the current framework effectively identifies trade-offs and synergies, it does not assess the optimal set of 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 (see, for example, Ezici et al.[34]). This enhancement would allow for the identification of the most effective circularity interventions tailored to specific contexts. Moreover, 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 and 3 of the framework, policymakers' insights can be incorporated into scenario development and data harmonization processes, enhancing the framework's reliability and utility.

Dynamic aspects are also important considerations in the assessment of circularity interventions. While the current framework does not address temporal dynamics, future iterations could integrate dynamic models such as dynamic MR EEIOA or dynamic Material Flow Analysis[35–37]. This would enable the identification of temporal changes in trade-offs and synergies, providing valuable insights for long-term planning and decision-making. Furthermore, the linear nature of the MR EEIOA model may not capture potential non-linear relationships present in circularity interventions. For instance, certain sectors may exhibit non-linear responses to interventions, requiring the application of non-linear models. Despite this limitation, the systematic steps outlined in the MR EEIO-based framework can still guide the identification of winners and losers, serving as a valuable tool for decision-makers.

Beyond the technical advancements proposed in this framework, the main contribution of this work lies in its ability to facilitate communication of circularity trade-offs and synergies to policymakers. By providing a step-wise process (including a Python code that facilitates the use of the MR EEIO-based 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.

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Competing interests

The author declare no competing interests.

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