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Rethinking environmental benefit allocation in industrial symbiosis

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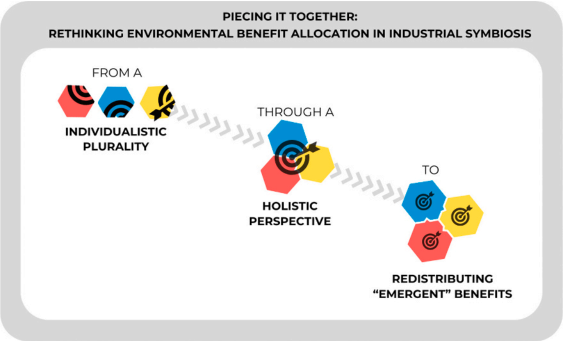
HIGHLIGHTS

- A new redistribution of environmental benefits in Industrial Symbiosis is proposed.
- The holistic approach aligns enterprise improvements with overall system gains.
- The method avoids the fragmentation issue in IS benefit assessment.
- The environmental benefits are seen as emergent properties of the IS network.
- Allocation is shifted from Life Cycle Inventory to Life Cycle Impact Assessment.

GRAPHICAL ABSTRACT



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ABSTRACT

Industrial Symbiosis (IS) enables enterprises that typically operate independently to collaborate through the exchange of energy, materials, services, and knowledge. This approach helps reduce reliance on virgin resources, minimize waste, and contribute to climate change mitigation, among other impacts. Recently, the potential of this approach has gained attention, as policymakers are integrating IS into ambitious targets, such as 2050 climate neutrality. Moreover, initially mainly driven by cost savings, now IS is valued for its environmental gains.

This shift has sparked interest in quantifying the advantages to both the overall network and individual enterprises. However, a standardized method for assessing these benefits has yet to be established.

Most of the current methodologies found in literature and guidelines take a reductionist approach, addressing the multifunctionality issue in IS by isolating one or a few enterprises at a time, thus fragmenting the complex system. This approach, which focuses on identifying 'who benefits' among the enterprises involved in IS, overlooks the complexity of the entire system. To address the tension between the need for a systemic perspective and the desire to quantify each enterprise's contribution and environmental gains, this study proposes a new redistribution approach. This approach ensures that each enterprise improves its score in line with the overall rate of improvement in the industrial symbiosis, compared to a scenario where no symbiotic practices are implemented. This approach is based on the idea that, regardless of the types of products and organizations involved, the environmental benefits of IS are emergent properties of the entire industrial symbiosis network, a composite system. That is why rather than focusing on inputs, this approach redistributes the overall benefits and

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impacts across the network, shifting the allocation process from the Life Cycle Inventory stage to the Life Cycle Impact Assessment stage.

1. Introduction

Industrial Symbiosis (IS) is a practice that builds interfirm exchanges of energy, utilities, materials, services, and knowledge among enterprises that are typically separated to create competitive advantages (Chertow, 2000; Lombardi and Laybourn, 2012). This practice is intended to optimize resource efficiency: it minimizes the use of raw materials and energy by utilizing one enterprise's production residue (a material not deliberately produced in a production process that may or may not be a waste (European Commission et al., 2012) as another enterprise's productive input (Chertow, 2000), making it a symbiotic resources. Hereafter, we refer to symbiotic resources as an input that substitutes a conventional raw material.

The practice of IS is rapidly gaining momentum worldwide. It has been enforced at various policy levels, from local to international, and in multiple forms, e.g. top-down government mandates and bottom-up independent projects and programs (Cecchin et al., 2020). The European Union (EU) has identified IS as a vital component of its strategy to become the world's first climate-neutral continent by 2050, making IS a critical element of the EU Sustainable Industry Policy Program (European Commission et al., 2018) and the Green Deal (European Commission, 2019). The European Commission is placing growing emphasis on the enterprises' responsibilities for their environmental performance (European Commission, 2020). Against this background, enterprises, initially driven by cost savings, now also value IS for environmental gains (Ormazabal et al., 2018).

Partaking into an IS can bring environmental benefits both to the overall system and to the individual enterprises, potentially supporting environmental claims. An enterprise supplying a production residue may claim the credit for reducing the demand for virgin material, while the enterprises receiving and reusing the production residue might want to market their product as having a lower environmental impact (Kristensen et al., 2021). Understanding how much an enterprise gains or contributes to the IS network's environmental performance can provide a strong incentive for opting for symbiotic resources. This justification can support any necessary modifications to the production chain or additional costs required to join the network (Arce Bastias et al., 2023). Since the primary drivers and implementers of the IS network are the participating enterprises (Tao et al., 2019), quantifying the environmental benefits of an IS—both from a system perspective (network-wide) and an enterprise perspective (individual enterprises)—has become increasingly important to these enterprises (Kerdlap et al., 2020).

The methods and indicators applied to evaluate an IS network's environmental impacts are various: Input-output analysis, ecological network analysis, Life Cycle Assessment (LCA), environmental impact assessment, carbon footprint analysis, material flow analysis, exergy analysis, emergy evaluation, and Ecological Footprint evaluation (Neves et al., 2020). Among these, LCA, a method based on accepted scientific standards and guidelines, clearly shows how networking reduces overall the demand for virgin raw materials, energy, and landfill waste disposal and their related environmental impacts (Brondi et al., 2018; Røyne et al., 2018; Neves et al., 2020). Even if there are many studies in literature that focus on the environmental performance of the overall IS network (Neves et al., 2020), only few have attempted to determine how the environmental performance of each enterprise changes due to partaking in the symbiotic network as it is a challenging step: the IS network is, by definition, a group of multiple enterprises—each producing its own main outputs and usually one or more symbiotic resources—making both the network and its participants inherently multifunctional (a system is multifunctional when it provides multiple functions (Ekvall and Finnveden, 2001)). Many scientific articles, reviews, and opinion papers discuss the existing solutions to handle multifunctionality, i.e. allocation methods, aiming to suggest how LCA practice can improve consistency. It is worth mentioning Pelletier et al. (2015), Hanes et al. (2015), Schrijvers et al. (2016a), Schrijvers et al. (2016b), Ijassi et al. (2021), Guinée et al. (2021), Schrijvers et al. (2021), Schaubroeck et al. (2021), Schaubroeck et al. (2022). Some articles specifically investigated how to solve the multifunctionality issue in order to address the redistribution of impacts among the enterprises involved in IS network and circular systems – see, for example, Van Berkel (2010); Martin et al. (2015); Kim et al. (2018); Arce Bastias et al. (2023); Ruini et al. (2025). Along with them, there is a wide array of standardized LCA guidelines, such as protocols (WRI and WBCSD, 2011), International Life Cycle Assessment Handbook (ILCA, 2015), Product Environmental Footprint - PEF (European Commission, 2013), and ISO 14044 (2006), that offer different ways to deal with the issue.

Table 1 summarizes the most used allocation methods to assess the impact of the enterprises involved in a IS network, outlining their main advantages and disadvantages regarding multifunctionality and the approach on which they are based, i.e. attributional or consequential. The attributional approach aims to quantify the existing impacts of a system through a retrospective and cause-oriented study (Tillman, 2000). The consequential, instead, looks ahead and assesses the variation in environmental exchanges resulting from implementing an IS (Schaubroeck et al., 2021). For an overview of the differences between the attributional and consequential approaches in dealing with multifunctionality issues within circular systems the reader can refer to Schaubroeck et al. (2021).

The aim of Table 1 is to provide a concise overview, not an in-depth analysis. For more detailed information, please refer to the relevant literature reviews, including those previously cited and Schrijvers et al. (2016b, 2016a), Moretti et al. (2020), Guinée et al. (2021), Lai et al. (2021).

After reviewing the literature, it appears that there is no one-size-fits-all method to capture each enterprise's role in IS network environmental performance, nor is there a standardized method or framework. This results in a struggle to agree on how to attribute the environmental advantages driven by the IS network to each enterprise in the IS network (Russell, 2019). In this context, justifying attribution becomes complex and can result in misleading environmental claims or "greenwashing" (Schrijvers et al., 2021). As noted by Ruini et al. (2025), when multiple enterprises within an IS network seek to claim environmental benefits resulting from material upcycling and resource sharing, they face a lack of consistent guidance. The most widely used LCA frameworks—the Greenhouse Gas Protocol, ISO standards, and the PEF—each propose different procedures, leading to significant variation in results. These inconsistencies can influence how environmental benefits are reported and may even affect enterprises' willingness to join or invest in IS networks. Furthermore, most of these procedures were clearly explained only for products that have reached the end of their life cycle and require disposal or reintegration into a new cycle. As such, it is sometimes unclear how to apply them on exchanges of residues typical of industrial symbiosis, where materials are diverted from waste streams and reused before becoming waste. An example is the circular formula in PEF. The formula is well described and applied to product at the end of their life, but no concrete example is provided for managed residues, making its application uncertain (Ruini et al., 2025).

According to Voinov and Farley (2007), and later to Bastianoni et al. (2023), sustainability should be assessed from a systems perspective. Focusing solely on individual enterprises (or pairs of enterprises), as in an enterprise perspective, may undermine the benefits of cooperation

Table 1
Most common methods dealing with multifunctionality in LCA, as highlight by and Guinée et al. (2021), Lai et al. (2021), Moretti et al. (2020), Schrijvers et al. (2016b, 2016a).

Allocation method	Key aspects	Main advantages	Main disadvantages
Subdivision	Divides a multifunctional process into sub-processes and collects data for each sub-process (ISO 14044:2006). Based on an attributional approach.	Avoids allocation issues and provides more detailed environmental information.	Rarely fully applicable; often it is not possible to subdivide the system.
System Expansion	Expands system boundaries to include all co-functions within the same boundaries (ISO 14044:2006). Based on an attributional approach.	Provides system-level results and avoids allocation.	Does not provide detailed information for individual co-products.
Substitution (System Expansion by Avoidance	Expands the system to account for co-functions by introducing substitutional production systems for non-primary functions, subtracting their impacts. It can be applied under both consequential and attributional approaches (Dalgaard et al., 2008; Schrijvers et al., 2016a)	Reflects real-world consequences.	Has high uncertainty due to assumptions about substitution; does not align with ISO 14044.
Physical Relationship Partitioning	Allocates burdens based on measurable physical relationships (e.g., mass, energy, or other physical properties) (ISO 14044:2006). Based on an attributional approach.	It is simple and often data-efficient; It aligns with causal relationships when physical dependencies exist.	May not reflect actual environmental impacts; It is limited to scenarios with clear physical relationships.
Economic Partitioning	Allocates burdens in proportion to the economic value of outputs (ISO 14044:2006). Based on an attributional approach.	Reflects market conditions and socio-economic context.	It is sensitive to market fluctuations; often fails to reflect environmental causality.
Cut-Off Approach	Assigns all environmental burdens to the main products, while other outputs leave the system as "burden-free" (Ekvall and Tillman, 1997). Also known as the 'recycled content approach' or '100–0 method.' Based on an attributional approach.	It is simple and widely used in attributional LCAs; avoids complex calculations.	Does not account for recycling benefits or future uses; underestimates long-term environmental effects (Schrijvers et al., 2016b)
End-of-Life Recycling Allocation	Attributes benefits to the producer since primary material production is avoided. Also known as the 'avoided burdens' approach (Heijungs and Guinée, 2007) 'recyclability substitution' (European Commission, 2010), 'closed-loop approximation', or '0–100 method'(Giorgi et al., 2017)	Reflects actual recycling rates and their impacts; is suitable for open-loop recycling.	May be inconsistent across different material loops; requires detailed tracking of recycled content and losses.
Waste Mining	Applies to residues with an unconstrained supply; attributes benefits to the consumer by avoiding waste management in the residue's life cycle (Ekvall and Tillman, 1997)	Avoids waste management burdens.	May lack reliable data in practice.
50/50 Method	Combines allocation to both recycled content and avoided primary production in equal proportions (Schaubroeck et al., 2021)	Balances both production and recycling perspectives; increases consistency for recycling scenarios.	May not align with specific LCA goals or accurately reflect market impacts.

(Figge et al., 2021) and fail to capture the true environmental advantages of the symbiotic network. However, it is fundamental to highlight the competitive advantages that each enterprise can gain from networking to secure the enterprises' interest in the IS (Kerdlap et al., 2020). To address the issue, we propose a novel approach based on LCA that shifts the allocation procedure from the Life Cycle Inventory phase to the Life Cycle Impact Assessment stage, redistributing the IS network's environmental benefits and impacts among its enterprises in a holistic manner. This approach is based on the idea that the IS network is a complex, interconnected system, with its environmental benefits arising as emergent properties.

The proposed approach addresses a real-world question increasingly often raised by enterprises considering participation in industrial symbiosis (IS) networks: What environmental benefits can I claim for my enterprise? This question becomes especially relevant when a symbiosis network is introduced through top-down initiatives—such as territorial policies or pilot projects led by public institutions, consultancies, or companies promoting circular economy practices in a specific region: the proposed approach can be a useful tool for circular economy managers.

The next sections are organized as follows: Section 2 covers the proposed methodology, and Section 3 explains the rationale for the new allocation approach with a numeric example. Section 4 discusses its novelty, challenges, and implications. Lastly, the conclusions present the main findings and their significance. Annex 1 presents a list of terms used in this paper, each accompanied by a specific definition and, where applicable, an acronym.

2. Material and methods

The proposed approach employs LCA, a widely used tool for assessing resource savings and environmental performance in IS networks (Daddi et al., 2017; Wadström et al., 2021; Arce Bastias et al., 2023; ISO 59020, 2024), to quantify the Environmental Benefits (EBs) of an IS network. EBs are defined as the environmental impacts avoided by the IS, including the impacts associated with the additional processes and inputs required to implement it, such as transportation and extra residue processing (Fig. 1). A common method to determine the overall EBs of an IS is to compare the environmental impact of the entire IS network, with a reference scenario, usually a linear scenario "where no circularity takes place" and where "there is no recirculation of energy and materials among enterprises" as defined by Bastianoni et al. (2023).

There are many examples in literature that aim to assess the impacts and benefits of a IS network based on it comparison with a linear scenario. See, among the others Sokka et al. (2008), Van Berkel (2010) Sokka (2011); Mattila et al. (2012); Martin et al. (2015); Kim et al. (2018); Martin and Harris (2018); Arce Bastias et al. (2023); Bastianoni et al. (2023); Ruini et al. (2025).

These examples helped to coherently define and model the reference scenario of a IS, also to compare alternative designs, as illustrated by Sokka (2011). Among the others, Martin (2015) recommended creating the reference scenario based on the current system's information and geographical data; it is essential to provide detailed explanations and justifications for all assumptions made when developing the reference scenario, such as materials used, energy consumption, transportation options, and other factors. Furthermore, Aissani et al. (2019) produced a comprehensive review on the topic of reference scenario for the IS.

Once the reference scenario(s) have been properly defined, it is essential to ensure comparability between the IS and the linear scenario (s) by setting the same functional unit and system boundaries (ISO, 2006). However, this task can be challenging. From a system perspective, an IS network is inherently multifunctional, delivering a variety of products with distinct functions. Each enterprise within the network produces its own main products—defined as the principal outputs of its production process—as well as residues. Some of these residues become symbiotic resources exchanged among enterprises, making the IS network a multifunctional system composed of interrelated multifunctional sub-systems (i.e., the participating enterprises). According to ISO 59020 (2024), IS can be considered an example of aggregated partial systems that integrate into a larger inter-organizational system.

In this context, Martin et al. (2015) recommend setting the functional unit as the sum of the main products of the involved enterprises—namely, those that determine the output of each production process (Weidema, 2000). This approach is supported by Bastianoni et al. (2023), who reached similar conclusions in the context of evaluating system circularity.

Once the functional unit is established, the next step is to define the system boundaries. According to Martin et al. (2015), the system boundaries of both the IS network and the reference scenario(s) should include all indirect upstream impacts—such as those from raw material extraction and transportation—as well as the direct impacts of the production processes themselves.

3. The proposed approach

In the proposed approach, the assessment of the overall EB is similar to most of the existing LCA methods. It starts from an existing IS with material and organizational linkages between the different enterprises constituting the symbiosis, as already defined by Aissani et al. (2019), as a current IS, and compares it with its corresponding linear scenario, a Hypothetical NonSymbiotic Reference Scenario (HNSRS) (Aissani et al., 2019). HNSRS does not represent the current industrial processes but a hypothetical scenario with no symbiotic exchanges between the enterprises involved (Aissani et al., 2019) – see Error! Reference source not found.

To identify and quantify the EB of a current IS, the approach compares the impact of the current IS with that of its HNSRS.

In line with this, the proposed approach models the HNSRS as the linear system that existed before implementing circular practices and imposes to collect data about it. In this way, the HNSRS can be defined based on both an in-depth understanding of how the linear system operated and on-site data, resulting in reasonable assumptions. However, using a reference scenario leads to a variability issue that should be addressed by performing a sensitivity analysis (as recommended by ISO standard 14044, 2006).

To ensure comparability between the systems, the current IS and HNSRS present the same functional unit – the sum of the main products of the IS – and the same system boundaries. In line with Martin et al. (2015), the system boundaries of the current IS is defined as "cradle to gate" including all the upstream system of the enterprises involved, their direct and indirect impact during production, as well as all the additional process necessary to turn the residues into symbiotic resources and the management of the residues that remain unused (i.e., not used even in the IS). The HNSRS is the set of single independent enterprises acting in a linear way. The system boundaries for the HNSRS are "cradle to gate" and it is necessary to clearly define the adopted residue management practices. Clearly defining the residue management practices used in the IS and linear scenario(s) helps to capture changes in the impacts related to the transportation, treatment, and utilization of residues or symbiotic resources. On the other hand, since the IS aims to repurpose production residues currently unused or utilized differently, in both scenarios, the main products of the involved enterprises remain unchanged, ensuring comparability.

In both the HNSRS and the current IS, the "end of life" stage of the main products is neglected as they are assumed to be the same in both the current IS and HNSRS, as per the definition of functional unit. If this was not the case, the end-of-life stage should be included.

When implementing symbiotic measures that involve a previously used residue (see Fig. 2), it is essential to assess whether the new network enhances the environmental performance of the overall system. This can be achieved by expanding the system to include the process that is already utilizing the studied residue. In this case, it is important to introduce a scenario, distinct from the HNSRS, that considers the previous use of the residue: the Previous IS scenario. All scenarios must account for both the enterprises involved in the Current IS network and those from the previous IS network, as well as any processes that have adapted to fit the Current IS (see Fig. 2).

A detailed discussion about the selection of the most appropriate method, i.e., attributional or consequential, is provided in the section titled "Methodological challenges" below.

After ensuring comparability, the approach proceeds with the Life Cycle Impact Assessment (LCIA) for both the current IS and HNSRS. The LCIAs are then compared and subtracted from one another, impact category by impact category, to evaluate the EB that the IS network has gained for each category, resulting in a list of EB, one for each category. The use of a single indicator (e.g., through aggregation and/or normalization) is avoided in order to quantitatively show the cumulative consequences of the IS symbiotic exchanges on the different impact categories and highlight potential trade-offs, as suggested by Bastianoni et al. (2019, 2023). By trade-offs, we refer to simultaneous changes in

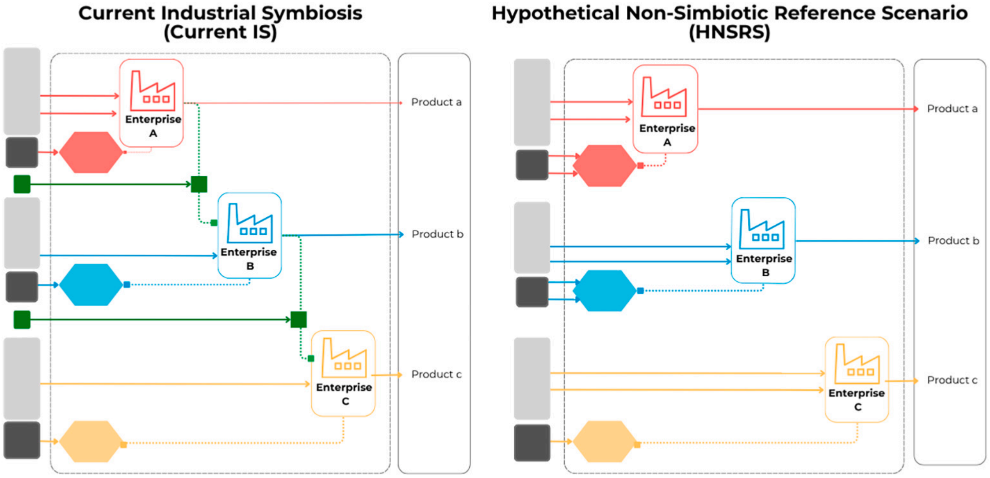

Fig. 1. A simplified graphical representation of Industrial Symbiosis (IS) and related linear scenarios involving three enterprises: Enterprise A, Enterprise B, and Enterprise C, producing Products a, b, and c, respectively. Hexagon represents processes for handling waste and residue. Light gray boxes indicate production inputs, while dark gray boxes represent inputs for managing waste. Green boxes highlight additional inputs specific to the IS scenario, including transportation and extra residue processing, light green boxes that represent co-products.

different impact categories that may go in opposite directions. For example, a symbiotic exchange that reduces GHG emissions by substituting fossil fuels with biomass might simultaneously increase nutrient discharges into water bodies, thereby worsening eutrophication. The IS's EB for the impact category U (EB^U) is calculated as follows:

$$EB^U = -(U_c - U_H) \tag{1}$$

U_C indicates the impact assessed for the impact category U of the current IS, and U_H indicates the ones of HNSRS. The minus in the formula ensures that a reduction of impact from the linear scenario to the symbiotic one can be read as a benefit. When EB^U is positive, the symbiotic system performs better than the linear one at least for the selected impact category (i.e. U).

The choice of which impact category should be prioritized depends on local environmental priorities and political will. The IS will be defined as an advantageous practice for the impacts for which EBs is positive (>0). The next step would be redistributing the EB among the enterprises partaking in the symbiotic network.

4. Redistributing the environmental benefit among the industrial symbiosis enterprises

Redistributing the EB among the enterprises in the IS network is challenging: the IS network is, by definition, a group of multiple enterprises—each producing its own main outputs and usually one or more symbiotic resources—making both the network and its participants inherently multifunctional.

This study tackles this challenge by proposing a novel procedure to redistribute the EB among the enterprises in the IS network. The EB, as calculated in Eq. I, is the EB of the overall IS network and results from the interactions among all the enterprises involved, resembling the emergent property of a complex system. The cooperation among the enterprises is a necessary condition for the existence of an EB. Therefore, all IS enterprises should be considered co-responsible for reducing the environmental impact of the IS. This is why this paper proposes to consider each IS enterprise as co-accountable for the EB. Thus, it imposes that each enterprise improves at the same rate, which is equal to the overall rate of improvement of the entire IS compared to the HNSRS. The percentage of improvement is equal to the overall rate of improvement of the IS system compared to the HNSRS, for each impact category.

For the category U, the percentage of improvement (I^U) of the current IS is calculated as follows:

$$I^U = \frac{EB^U}{U_H} * 100 \tag{2}$$

where U_H indicates the impact assessed for the impact category U of the HNSRS and EB^U is the IS's EB for the category U, as defined above, Eq. (1).

The approach provides the EB for each impact category assessed, resulting in a set of I for the single IS's enterprises and the overall IS.

4.1. *A simplified system to illustrate the proposed approach*

A simplified system illustrates the rationale behind the proposed approach featuring a current IS with its HNSRS, see Fig. 3 and Table 2. It involves three enterprises—Enterprise A, Enterprise B, and Enterprise C—each producing distinct products (Product a Product b, and Product c, respectively).

Fig. 3 shows various inputs: inputs 1 to input 6 are related to production resources, while inputs v to z are required to manage residues and wastes. Inputs 7 and 8 are specific to the current IS. They are related to the additional processes and inputs necessary to make the IS network possible – for instance transport and additional residue processing (green boxes). Inputs w and y are the inputs necessary for processing residue in the HNSRS when they are not used as symbiotic resources while input v, x and z are still necessary also for the IS. For the sake of simplicity and to enhance the clarity of the example, it is assumed that the implementation of industrial symbiosis fully replaces some waste management flows (i.e., Inputs w and y in Fig. 3) and the production processes of products b and c (Inputs 4 and 6 in Fig. 3).

In the HNSRS, Enterprise A uses inputs 1 and 2 for its production process while input v and w are the material and energy flow necessary to treat its production residue and waste. Enterprise B uses inputs 3 and 4 for its production process, while x and y are used to treat its production residue and waste. Enterprise C uses inputs 5 and 6 for its production process, while input z is used to treat its production residue and waste.

The current IS system has an impact of 1300 units, while the related HNSRS has an impact of 1575 units.

The IS system performs 17 % better than the HNSRS, with a difference of 275 units, see Table 3.

The proposed approach assigns to each sub-system a 17 % improvement rate over the performance of its corresponding HNSRS counterpart for the selected impact category U. Table 4 shows each subsystem's impact in the HNSRS and current IS, as well as the assigned improvement, the sums match the system's totals.

As shown in Table 4, enterprise A improves its performance by 131 units, enterprise B by 96 units, and enterprise C by 48 units. The proposed approach provides each enterprise a benefit based on the overall environmental performance of the system: each enterprise's environmental performance improves proportionally to the IS.

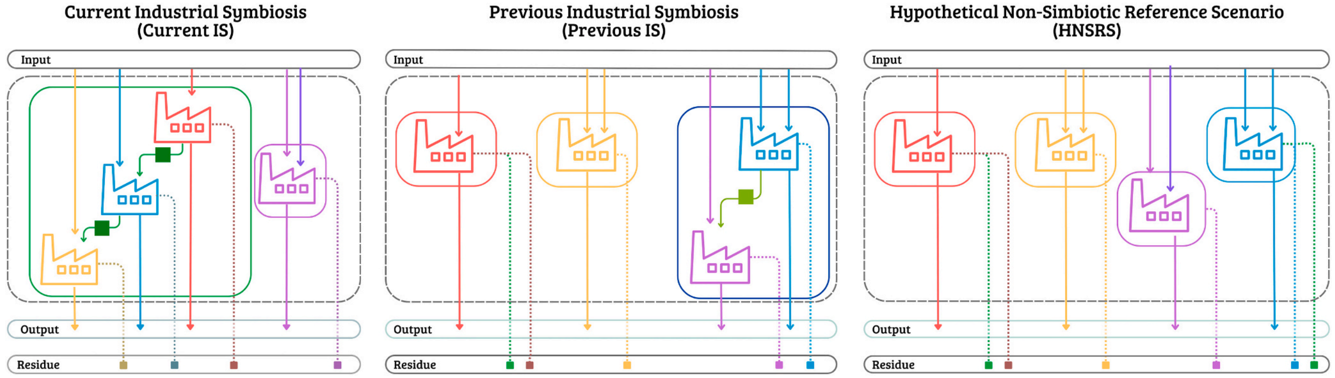

Fig. 2. This example illustrates the "HNSRS" and "Previous IS" scenarios, where the past structure of the system is taken into account along with the corresponding Current IS. The dotted line represents the system boundaries of the LCA study, which is consistent across all three scenarios. The solid line delineates the boundaries of the productive systems considered. In the Current IS scenario, the system consists of two components: the current IS (green) and an additional enterprise (purple). For the Previous IS scenario, the previous IS (blue) is considered along with two enterprises from the current scenario (red and yellow). In the HNSRS scenario, each enterprise operates independently.

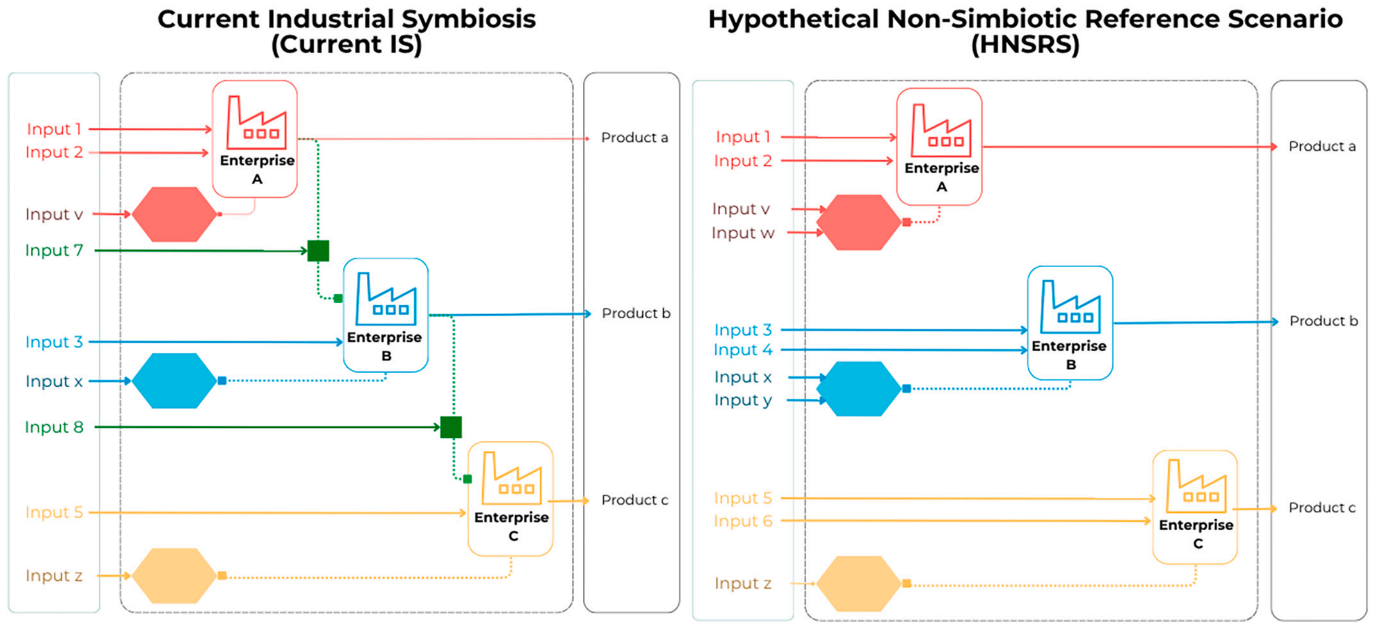

Fig. 3. Current IS and the corresponding HNSRS, the Hexagon represent the processes necessary to treat waste and/or residue.

Table 2
The impacts related to the inputs to the overall system for a generic impact category (U) in the Current IS scenario and in the HNSRS respectively "u" is the unit of measure of the generic impact category U.

Input		Impact (U) Current IS	Impact (U) HNSRS
Production resources	Input 1	250 u	250 u
	Input 2	200 u	200 u
	Input 3	200 u	200 u
	Input 4	0 u	100 u
	Input 5	50 u	50 u
	Input 6	0 u	25 u
Resources specific to the current IS	Input 7	100 u	0 u
	Input 8	50 u	0 u
Resources to manage residues and waste	Input v	150 u	150 u
	Input w	0 u	150 u
	Input x	100 u	150 u
	Input y	0 u	100 u
	Input z	200 u	200 u

It is possible to compare the results obtained by the proposed approach with some of the main allocation approaches presented in literature and suggested in guideline as ISO or GHG protocol listed in Table 1.

As show in Table 5 the choice of allocation method significantly influences how environmental benefits and burdens are distributed among the enterprises participating in the IS network, despite a consistent overall system improvement of 17 % compared to the HNSRS. Methods based on physical and economic partitioning lead to highly uneven outcomes: while Enterprise A benefits under physical allocation (+35 %), Enterprise C sees a worsening (−11 %); economic partitioning strongly favors Enterprise B (+38 %) but penalizes C (−44 %). In contrast, the Cut-approach shifts burdens to product producers, resulting in improvements for A (20 %) and B (27 %), but a worsening for C −9 %). The End-of-Life and 50/50 methods also show imbalanced effects, with B consistently burdened. The only method that seems to guarantee a win-win situation is the 0–100 approach. However, there is a significant imbalance in the benefits gained by different companies that can still access the information system network. This imbalance prevents a fair redistribution of the overall impact. These findings underscore the importance of allocation choices, as they can significantly influence perceptions of fairness and should be thoughtfully considered in assessments of industrial symbiosis. Coherent results on real case studies were obtained by Ruini et al. (2025) in a study that focused on how different guidelines, namely GHG protocol, PEF and ISO standard, norms the redistribution of the upcycling credit among the enterprises of a IS network. The present comparison does not encompass the System Expansion by substitution due to the fact that this method requires a carful definition of the substitutive system and it is usually used in consequential studies.

5. Discussion

5.1. Advantages of the approach

The literature presents various methods for addressing multifunctionality: some are based on stakeholder consensus aiming to promote a specific type of behavior. These include the Cut-Off Approach (or "100–0 method"), End-of-Life Recycling Allocation ("0–100"), and the 50/50 method. Other, such as partitioning methods grounded in physical relationships and the substitution approach (System Expansion by Avoidance), rely on empirical evidence. Economic partitioning falls somewhere between these two categories.

Regardless of the method used, all existing allocation criteria are determined by the LCA practitioner, with or without adherence to specific standards. Additionally, these methods typically analyze the IS network by fragmenting it into individual enterprises (i.e., partitioning based on economic and physical factors, as well as system expansion and System Expansion by Avoidance) or pairs of enterprises (using the cut-off approach, end-of-life recycling allocation, and the 50/50 method), adopting an individualistic perspective. The individualistic approach simplifies the IS – a composite system – into juxtaposed fragments. It aims to solve the multifunctionality issue of a complex system by first

Table 3
The overall system performance in the current IS and in the HNSRS, the overall variation calculated as per Eq. I reported in absolute value and in percentage.

	Current IS	HNSRS	EB^U	I^U
Total impact	1300 u	1575 u	275 u	17 %

Table 4
The impact of each sub-system in HNSRS along with the assigned improvement reported in percentage and in absolute value and the impact of each sub-system in the current IS.

Enterprises	Enterprises impact in HNSRS (u)	% of improvement	EB^{U}	Current IS
A	750 u	17 %	131 u	619 u
B	550 u	17 %	96 u	454 u
C	275 u	17 %	48 u	227 u
Total system	1575 u	17 %	275 u	1300 u

solving the single enterprise multifunctionality issue, seeking to determine "What benefit do I (enterprise) get?" (Martin et al., 2015). However, in this way, they fail to detect the results of all connections and relations that underpin a symbiotic system, detectable only through a systemic perspective (Figge et al., 2021). As discussed by Figge et al. (2021) regarding the eco-efficiency of circular systems (production per unit of resource use) and Bastianoni et al. (2023) concerning their environmental performance, decision-making processes based on individual indicators overlook the advantages of cooperation among enterprises. This oversight risks making symbiotic exchanges seem less efficient and less appealing. Some enterprises may face additional costs, which presents a significant barrier to establishing IS (Figge et al., 2021), as also shown in Table 5.

The proposed approach tackles the multifunctionality issue with a systems perspective. It shifts the EB assessment from the enterprise level to the system level through system expansion. It expands the system until it encompasses the entire IS. Consequently, the symbiotic resources never leave the IS system as output and, therefore, there is no need to subtract them from the inventory.

Based on the idea that the existence of the EB is contingent upon the collective symbiotic interactions among all enterprises involved in the IS, the EB can be defined as an emergent property of the complex system. The proposed approach redistributes the EB rather than the inputs of the IS, solving the multifunctionality issue of the single entity based on the overall EB and not vice-versa. This is possible by postponing the allocation from the Life Cycle Inventory (LCI) stage to the Life Cycle Impact Assessment (LCIA) phase. Each enterprise improves at the overall rate of improvement of the entire current IS compared to the HNSRS, providing a redistribution factor that reflects the physical relationship between the EB and the overall IS network regardless of the types of products and enterprises involved. This makes the proposed approach preferable with respect to other allocation methods: until now, no single criterion seems to have been able to provide logical partitioning for all types of products and organizations, and practitioners recommend different partitioning criteria depending on the subject studied (Curran, 2007). Moreover, the choice of the allocation criterion has a drastic effect on life-cycle impacts (Stamp et al., 2013) and, in some cases, it can be manipulated to achieve specific study objectives, undermining the overall credibility of the assessment (Hanes et al., 2015). To mitigate these issues, using multiple allocation methods has become common practice. However, this has not solved the problem as it leads to conflicting results, making it difficult to draw meaningful conclusions (Zaimes and Khanna, 2014). This is why the proposed approach is an efficient solution that helps draw meaningful conclusions without undermining the overall credibility of the assessment.

In the proposed approach, each enterprise improves at the overall rate of improvement of the entire IS compared to the linear scenario, providing a redistribution factor that reflects the physical relationship between the EB and the overall IS. The approach captures the different scale of the environmental impact of each enterprise partaking into the IS. The redistribution criterion allows a consistent attribution across enterprises based on such scale and differences. Accordingly, any over- or under-compensation is prevented as no enterprise will get exaggerated benefit, whether high or low. This is consistent with the fact that enterprises with higher emissions have a higher mitigation potential.

When an enterprise acts as an "anchor tenant" —connecting with multiple other enterprises while engaging in several symbiotic exchanges— two cases can be envisioned: 1) the networks are totally disconnected and they unite only within the enterprise (e.g. the production of an output and its packaging); 2) the networks overlap.

Table 5
The assigned improvement percentage for each sub-system and the overall current IS, calculated by applying the most common allocation method in literature, as listed in Table 1; the calculation is available in the supplementary materials.

Allocation method	Assumption	Improvement over the HNSRS (%)			
		Enterprise A	Enterprise B	Enterprise C	Overall system
Subdivision	It is not possible to perform subdivision	N.A.	N.A.	N.A.	N.A.
System Expansion	It is possible only to assess the overall IS network benefits and not the one for each enterprise	N.A.	N.A.	N.A.	17 %
Physical Relationship Partitioning	The mass proportion between product a and its residue is product a: residue =70:30 The mass proportion between product b and its residue is product b: residue =90:10	35 %	8 %	−11 %	17 %
Economic Partitioning	The economic proportion between product and its residue is product a: residue =80:20 The economic proportion between product b and its residue is product b: residue =70:30	25 %	38 %	−44 %	17 %
Cut-Off Approach (100−0)	The environmental burdens of Enterprise A is assigned to the main product a, while the residue leaves Enterprise A as "burden-free". The same goes for Enterprise B and its main product b and residue. The additional processes and inputs necessary to make the IS network possible, inputs 7 and 8, are attributed to the company that uses the residue. Therefore, inputs 7 is assigned to Enterprise B, and input 8 by Enterprise C.	20 %	27 %	−9 %	17 %
End-of-Life Recycling Allocation (0−100)	Attributes benefits to the producer since primary material production is avoided.	7 %	36 %	9 %	17 %
50/50 Method	The additional processes and inputs necessary to make the IS network possible, inputs 7 and 8, are split between the enterprises involved in the symbiotic exchanges, enterprise A -enterprise B and enterprise B -enterprise C, respectively.	13 %	32 %	0 %	17 %

In case 1 the multiple IS networks should be considered separately to account for the scale and the role that the enterprise plays relatively to each network, which could be higher for one (higher improvement share) and lower for another. If this separated application were not implemented, considering a single IS network might cause the unjustified reduction of the EB of one (or multiple) member of one IS. In numbers, if the anchor tenant would get a 10 % improvement in one IS network (together with all other members of the first IS), and it would get a 5 % improvement in a second one (together with all other members of the second IS), treating the expanded system as a unique IS network might cause attributing, for instance, a 7,5 % improvement to all members of the (expanded) IS network. This of course would favor the members of the second network and penalize the members of the first network, resulting inconsistent with the objective of the approach. Obviously, in the two separate assessments, the anchor tenant enterprise must present the same baseline emission. This allows the accumulation of the benefits from different networks in an additive fashion, still ensuring that no exaggeratedly low or high benefit is attributed to the anchor tenant – thus also avoiding negative balance.

In Case 2, where the networks overlap, the different IS networks should be integrated into a single, extended system. This integration is justified only if it results in a greater overall environmental benefit at the system level. Within this extended network, all enterprises — including the anchor tenant — are considered equally responsible for the collective outcomes. No additional credit is assigned to central players, nor are they disadvantaged. This approach promotes collaboration over competition in pursuing environmental improvements and supports the long-term development of stable and mutually beneficial symbiotic relationships.

5.2. Methodological challenges

The proposed approach addresses the methodological challenges faced in assessing the IS benefit thought LCA such as defining the hypothetical scenario and selecting the most appropriate approach—either attributional or consequential.

5.2.1. Definition of the hypothetical scenario

The selection of the reference scenario is essential for assessing the EB of the IS network, as clearly highlighted among the others by Van Berkel (2010); Sokka et al. (2011); Mattila et al. (2012); Martin (2015); Martin and Harris (2018); Aissani et al. (2019).

Uncertainty in the definition of the hypothetical scenario can be screened by means of a sensitivity analysis that will quantify the relevance of the various modeling choices. Such analysis could point out extreme cases (e.g., best and worst) that could be used as alternative linear scenarios to account for the uncertainty linked to the modeling choices. A possible option would be to use the worst case (i.e., lowest benefit) to adopt a conservative approach.

5.2.2. Attributional or consequential approach

We refer the reader to Schaubroeck et al. (2021) for an overview of the differences between the attributional and consequential approaches in dealing with multifunctionality issues within the circular systems. The proposed approach has been explained assessing the EB of an existing productive system. In this case the chosen approach has been the attributional: it quantifies the existing impacts through a retrospective and cause-oriented study (Tillman, 2000). The analysis considers the activities that contributed to the life cycle of the IS products, tracing them back in time using data on either specific or market-average suppliers. The results can be used to communicate to the enterprises involved and the public if and how much the IS has lowered the system's negative environmental impact.

However, the model is suitable also in prospective situations where an IS system does not exist (yet). Take, for example, the task of evaluating the benefits of implementing an IS system from scratch and assessing how each enterprise could contribute to those benefits. The new research question focuses on an IS that does not exist yet: it comprises possible linkages between current enterprises and hypothetical processes added to link enterprises, or the implementation of a whole IS in a given area. Aissani et al. (2019) define it as prospective IS.

In this case, the scenario used for comparison is a current industrial process with no symbiotic exchanges between the enterprises concerned (a business-as-usual scenario): a current nonsymbiotic reference scenario (CNSRS). In this situation, the LCA study is requested to provide the enterprise with information about the possible future environmental benefits of a choice.

Even if the proposed approach to redistribute the IS benefits among its enterprises remains applicable, it is essential to note the difference in terms of the obtained information. In the case of the original question, the approach provides information on the system's status quo and answers the question “What are the benefits obtained so far by each enterprise?”. In the second one, the approach looks ahead, assessing the future possible system performance; it answers the question “What will be the benefits obtained in the future by each enterprise?”

In the second case, a consequential LCA approach should be used, at least in the case when previous circular practices already existed. Consequential LCA looks ahead and assesses the change in environmental exchanges resulting from implementing an IS (Schaubroeck et al., 2021). Even under this condition, the proposed approach to redistribute the IS benefits among its enterprises remains applicable: after ensuring comparability between the IS and the CNSRS, the LCA proceeds, generating a LCIA for both the IS and the CNSRS. The LCIAs are compared and subtracted from one another, category by category, to evaluate the future EB that the studied IS could gain if such IS were implemented, in a prospective way.

The proposed approach, applied prospectively, adopting the consequential approach, considers all the changes the IS can cause. In this way, it detects any IS/circular measure that can cause environmental disadvantages to the overall systems, while still being able to assess an enterprise ‘s EB.

Applicability of the proposed approached in reference to other recent LCA guidelines.

The proposed approach is in line with many established methodologies in the literature regarding the assessment of the overall environmental benefits of IS network, while introducing a novel approach for redistributing these benefits among participating enterprises. It is also consistent with ISO standards, particularly ISO 14044:2006, which recommends allocation procedures based on physical relationships. In this approach, the EB is treated as a shared property of the IS network, emerging from the collective interaction among sub-systems. This reasoning applies both under attributional and consequential approaches.

Furthermore, the proposed approach aligns with the GHG Protocol Corporate Standard, which does not prescribe a fixed method for allocating emissions or reductions among multiple reporting companies, instead, it encourages the development of context-specific double counting policies (chapter 11, pp. 81–83) – i.e., policies that define how “two or more reporting companies should take ownership of the same emissions or reductions” (GHG Protocol Corporate Standard, 2004, glossary). In this regard, our approach offers a transparent and structured solution for fairly allocating shared EBs in IS networks.

By contrast, the proposed approach is not compatible with the circular footprint formula suggested in the PEF framework. The PEF's approach is reductionist, focusing on individual products or enterprises, and – inherently – does not allow for an expansion of system boundaries such as the one needed to capture the systemic and interconnected nature of industrial symbiosis. A more detailed study about the application of the circular footprint formula suggested in the PEF to IS was carried out by Ruini et al. (2025).

5.3. Limits of the approach and possible future advancements

It is important to note that EBs associated with IS can sometimes seem minor due to differences in scale between the overall environmental impacts of enterprises and the EBs generated through IS activities, as shown in some example by Ruini et al. (2025). As we transition towards circular production systems, the scale of EBs may seem limited, underscoring the necessity of this approach. While some may advocate for analyzing only the inputs altered between IS and linear scenarios, such a limited perspective would undermine the integrity of the redistribution process. EBs should be viewed as emergent properties of the entire symbiotic network, emphasizing the need for holistic evaluation.

A limitation of the approach may be the availability of data needed to assess overall environmental impacts. As noted by Bastianoni et al. (2019, 2023), access to robust environmental data is essential for effective policymaking and sustainability efforts, though it is not always readily available. However, in the context of top-down initiatives—such as territorial policies or pilot projects promoted by public institutions, consultancies, or enterprises—data collection is often more feasible also due to the fact that enterprises increasingly often have LCA-based certifications. These initiatives can offer a solid foundation for conducting environmental analyses. From this perspective, EBs derived from IS network are not limited to the IS network itself but may extend to the broader territory in which the network operates. Since IS is often embedded within wider territorial planning strategies, it is possible to quantitatively assess how the EBs of the IS mitigate the overall environmental impacts of the region as already suggested by Martin and Harris (2018). Although such applications fall outside the scope of this study, they offer promising avenues for future research.

The proposed approach assesses multiple environmental impact categories, selected from widely used LCA characterization methods. These categories include global-scale impacts, such as climate change and ozone depletion, as well as regional-scale impacts like acidification and eutrophication. This allows for a quantitative assessment of the cumulative effects of industrial symbiotic exchanges and helps identify potential trade-offs across different impact categories.

However, interpreting regional impacts requires caution, especially in geographically extensive IS networks, where the effects in one area may differ significantly from those in another. This poses a usability challenge, as decision-makers must contextualize the list of environmental benefits based on the specific system and territory under study. Moreover, trade-offs are not restricted to LCA categories, which primarily focus on flows from the Technosphere. It is also essential to consider impacts and benefit related to the biospheric resources, as well as economic and social dimensions (Martin and Harris, 2018). These aspects are better assessed using complementary accounting methods, such as emergy evaluation (Oliveira et al., 2021) for biospheric resource use, Environmental and Societal Life Cycle Costing (Kambanou, 2021), and Social Life Cycle Assessment (Sokka, 2011). While the foundational principles of the proposed method could be adapted to incorporate these broader impacts and benefits, such applications are beyond the scope of this study and warrant further investigation in the future.

6. Conclusion

A shift from an individualistic to a systemic perspective is necessary to address the multifunctionality issue within industrial symbiosis. The proposed approach enables the assessment of each enterprise's environmental benefits by recognizing the interconnectedness among them and promoting an equitable distribution of overall environmental benefits. This comprehensive approach captures the effect of interactions among enterprises, ensuring that all can benefit from collaboration, thus enhancing the overall attractiveness of the industrial symbiosis. The reductionist approach of the previous methods does not always bring a win-win situation to all the enterprises of the IS, when the implementation of the IS network secures an overall environmental benefit. The absence of a proper distribution of environmental benefits among the enterprises limits the attractiveness of creating the network; as such, a choice might appear disadvantageous for potential participant enterprises. Without any clear benefit, enterprises struggle to justify adapting to symbiotic resources possibly linked with production changes or additional costs. Fragmenting the symbiotic system fails to fully capture the interactions among stakeholders and policymakers that occur across different markets and regulatory conditions.

By promoting a holistic view of multifunctionality, this new approach encourages greater cooperation among enterprises and facilitates the transition from a linear ‘take-make-dispose’ model to a more circular approach.

CRediT authorship contribution statement

Anna Ruini: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Fabio Sporchia:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Valentina Niccolucci:** Writing – review & editing, Validation, Methodology, Formal analysis. **Federico M. Pulselli:** Writing – review & editing, Validation, Supervision, Investigation. **Simone Bastianoni:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used the Grammarly software (premium version) and ChatGPT (4o mini version) in order to spell and grammar check the article and make the test as fluent as possible. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Declaration of competing interest

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

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Annex 1

Table 6
List of terms, definition and acronym.

Term	Definition	Acronym
Industrial symbiosis	A practice that builds interfirm exchanges of energy, utilities, materials, services, and knowledge among enterprises that are typically separated to create competitive advantages (Chertow, 2000; Lombardi and Laybourn, 2012).	IS
Production residue	A material not deliberately produced in a production process that may or may not be a waste (European Commission et al., 2012)	
Symbiotic resources	One enterprise's production residue that is utilized as another enterprise's productive input that can substitute a conventional input.	
Environmental Benefits	The impacts that circular practices have avoided minus the impact linked to the additional processes and input necessary to make the IS possible such as transport, additional residue processing and so on, from now on added impact of the added processes	EB
Emergent property	Emergent properties are properties that a complex system has but its individual components such as underlying modules and subsystems do not have (Šarić et al., 2017)	
Linear system	Scenario "where no circularity takes place", and "there is no recirculation of energy and materials among them" as defined by Bastianoni et al. (2023)	
Multifunctional system	A multifunction process is an activity that fulfils more than one function	
Multifunctionality issue	An issue regarding the apportionment of the environmental burden to each co-function/co-product (Ekvall and Finnveden, 2001; Lai et al., 2021)	
Current IS	An existing IS with material and organizational linkages between the different enterprises constituting the symbiosis (Aissani et al., 2019)	
Hypothetical NonSymbiotic Reference Scenario	A hypothetical scenario with no symbiotic exchanges between the enterprises involved (Aissani et al., 2019)	HNSRS
Current NonSymbiotic Reference Scenario	A current industrial process with no symbiotic exchanges between the enterprises concerned (a business-as-usual scenario) (Aissani et al., 2019)	CNSRS

Annex 2. Supplementary data

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Data availability

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

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