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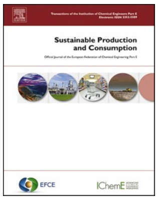

Closing the loop: Structural, environmental and regional assessments of industrial symbiosis

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ABSTRACT

Regional symbiosis, based on industrial symbiosis principles, is one possible strategy for managing the environmental impact of human activities and the increasing risks associated with resource availability. An assessment is needed to ensure the benefits of implementing synergies in a region. Current research focuses on the environmental and structural analysis of symbiosis networks but lacks frameworks that consider the benefits of symbiosis at the regional scale. By combining ecological network analysis (ENA), circularity metrics and the life cycle assessment (LCA) approach, this study intends to analyze the benefits brought by expanding industrial symbiosis to a broader region. Through the analysis of different symbiosis scenarios under two energetic cases (electricity and biomethane production), the study showed that implementing regional symbiosis was a lever to improve the robustness, the circularity and the environmental impact of the system. The environmental dimension was lowly affected by the scenario changes, but they provided a wider effect on regional metrics. The change in energetic production did not bring significant differences in the results. This study also showed that the structural metrics followed a different trend than the regional and environmental metrics, revealing the complementary views that were brought by the multidimensional analysis. It advocates for a holistic assessment of systems and highlights network structural organization, which should be accounted for in regional sustainability planning.

1. Introduction

Many regions, especially urban ones, are highly dependent on external resources to support their economies (Wiedmann et al., 2015). These resources come from hinterlands sometimes located thousands of kilometers away from their final consumption areas (Kim and Barles, 2012). Consequently, urban regions face increasing risks regarding the future availability of resource supply, considering the combined effects of various global threats such as climate change (Feiferytė-Skirienė and Stasiškienė, 2021) and geopolitical and economic crises (Hayashi and Hughes, 2013). Therefore, these regions need to implement strategies to increase their resilience with regard to resource supply while mitigating the effects of their activities on the natural environment (IPCC, 2007).

The regional scale, comprising the city and its close hinterlands (a few hundreds of kilometers), is appropriate for considering opportunities for systemic transformations (Brunetta et al., 2019; IPCC, 2022) that entail new ways to organize activities. Among these opportunities, urban-industrial symbiosis (UIS) has been identified as a promising solution (Feiferytė-Skirienė and Stasiškienė, 2021; Fraccascia, 2018). The UIS concept is an extension of the industrial symbiosis concept (van Berkel et al., 2009) and is one of the strategies identified in the circular economy approach (Murray et al., 2017). Industrial symbiosis refers to networks of various organizations that exchange materials, energy and/or water flows in the same geographic area. The “symbiosis” term refers to the relationships that can take place in nature, when different species exchange material, energy or information. Doing so, industrial actors can benefit from the exchanges to gain competitive advantage collectively, rather than individually (Chertow, 2000). Furthermore, industrial symbiosis networks operationalize the concept of “closing the loop” at the scale of different organizations, e.g., the waste of one company is used as a resource by another (Erkman, 1997). These efforts contribute to creating closer resource supply chains for industrial activities and help to establish interfirm relations that translate into eco-industrial parks (Chertow, 2000). UIS systems rely on the same principle and are mainly based on waste exchange, the urban area providing industrial

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Nomenclature

Acronyms

AMI	Average mutual information
ENA	Ecological network analysis
FEP	Freshwater eutrophication potential
GWP	Global warming potential
TAP	Terrestrial acidification potential
UIS	Urban-industrial symbiosis

Variables and parameters

C	Circularity index
D	Dependency index
H	Shannon index
R	Robustness
q_f	quantity of flow *f*
s_{mf}	impact score of material flow *f*
s_{tf}	impact score of transportation of flow *f*
t_f	transport of flow *f*
t_{ij}	flow coming from actor *i* to actor *j*
$T_{..}$	sum of flow t_{ij}

actors with secondary materials used as inputs (van Berkel et al., 2009). The urban area can also be the recipient of industrial products (e.g. energy), as in the Kalundborg case where municipal heating comes from industrial actors nearby (Valentine, 2016). Due to the broader type of actors that can be considered in UIS, those systems can also include additional activities such as agricultural clusters embedded with more traditional sectors such as manufacturing and utilities (Morris et al., 2020; Neves et al., 2020).

Similar to the industrial symbiosis, the UIS are expected to bring benefits that need to be evaluated. The UIS sustainability assessment is a multicriteria analysis that encompasses economic, environmental and social dimensions as well as symbiosis attractiveness and its potential for regional planning, innovation and territorial autonomy (Ogé, 2021). Nevertheless, most of the studies conducting assessments of UIS systems focus on the environmental and economic aspects (Fraccascia, 2018). The environmental benefits are assessed with the same methods used in industrial symbiosis assessment, i.e., life cycle assessment (LCA), ecological footprint, material flow analysis, exergy and emergy (Loiseau et al., 2012; Neves et al., 2020; Walzberg et al., 2021). The conclusions are similar to those drawn for industrial symbiosis systems: energy, material and water savings (Fujii et al., 2016; Sun et al., 2017) and CO_2 emissions reductions (Butturi et al., 2019).

Other studies have assessed UIS systems from the perspective of network organization. The most frequently used method is network analysis (Fraccascia and Giannoccaro, 2020; Neves et al., 2020), which focuses on interactions between different entities (Bodini, 2012). These studies have helped to assess industrial network vulnerability to external perturbations (Li et al., 2017), robustness (Wang et al., 2018b) or stability (Xiao et al., 2016). Among the network analysis methods and metrics, ecological network analysis (ENA) (sometimes called food web analysis) is of special interest because it presents the advantage of assessing a system in multiple dimensions, thus accounting for the complexity of any human–environmental system (Bodini, 2012).

Finally, even though UISs are necessarily linked to the region where they occur (Cerceau et al., 2018), few studies aim to characterize the influence of symbiosis on closing the loop at the regional scale, i.e., assessing its potential to act as an energy or material supplier for regional activities. To this end, circularity metrics can be useful since they quantify the recycling rates and the level of secondary and primary resource consumption, though mostly at the product or process levels (Circle Economy, 2020; Ellen MacArthur Foundation, 2015; Virtanen et al., 2019). There is, however, an opportunity to adapt these metrics to the regional level (Circle Economy, 2020; Ellen MacArthur Foundation, 2015).

Some authors proposed multidimensional analysis where they developed frameworks combining structural assessment with economic cost (Dave and Layton, 2020), environmental impact (Souza et al., 2019) or both (Dong et al., 2022). Nevertheless, there is a gap on the application of such frameworks at the regional scale, with a regional approach to symbiosis development. Considering this, the study develops a multidimensional analysis of a regional symbiosis modeled by a scenario approach that reflects industrial symbiosis integration into its surrounding region. More specifically, it proposes to compare different scenarios of an UIS network based on three criteria: the robustness of its organization (i.e., its structure), its environmental impact and its contribution to regional circularity. This approach allow us to gauge the effects of synergies on these three dimensions. Additionally, this type of analysis could provide insights into the relevance of integrating industrial symbiosis into regional planning. For example, this study considers the robustness of the network formed between the industrial symbiosis and other regional areas as well as its dependence on the supply of primary external resources.

The remainder of this paper is structured as follows: the literature review (Section 2) gives context on UIS networks and their assessment, the methodology (Section 3) gives details on the tools used for the regional symbiosis scenarios assessment; the results (Section 4) present the findings with an emphasis on the relative performances of the scenarios; and a discussion (Section 5) locates the results among the literature and provides perspectives for future research.

2. Literature review

This section introduces an overview of the UIS network types that are found in the literature and then focuses on the UIS assessment in terms of network organization, regional integration and environmental impact.

2.1. Urban industrial symbiosis network types

A snapshot of UIS cases is presented in Table 1, to highlight their features. The selected cases were chosen to reflect the type of networks that can be found in UIS literature. It was mainly based on the review papers by Neves et al. (2020), Fraccascia (2018) and Vahidzadeh et al. (2021), with a focus on studies published within the last ten years.

From the cases presented, UIS are mainly centered around industries and urban areas, mainly exchanging waste material and energy. The agricultural activity is not overly present in the referenced studies. Nevertheless, the review by Neves et al. (2020), which investigate around 100 cases, identified 35 cases considering agricultural activity. Furthermore, agricultural clusters have been identified relevant when it comes to UIS networks, as they allow to link urban areas and natural ecosystems (Dong et al., 2018). For example, Dong et al. (2017) proposed a framework for a comprehensive UIS integrating agricultural, industrial and urban areas to contribute to low-carbon urban planning achieved by local resource and energy supply, as well as waste management. Fraccascia et al. (2021) also propose to include agricultural clusters in symbiosis networks as they studied biomethane production at the regional scale: the agricultural cluster is seen as the provider of organic waste to feed a biogas plant, and the receiver of digestate and energy produced by the plant. The biogas plants (anaerobic digesters) are also presented as central actors in Fan et al. (2021) and Cortez et al. (2022) papers. This actor type allows for exchanges based on material synergies (from various actors to biogas plant) but also on energy synergies (from the biogas plant to various actors). The co-products of the energy production can also be used by the other actors, e.g. urban and/or agricultural (Albino et al., 2015; Fraccascia et al., 2021).

Table 1
Characteristics of selected urban industrial networks.

Reference	Case	Number and type of actors	Number and type of flow
Ohnishi et al. (2017)	Kawasaki, Japan	7 Urban and industrial activities, recycling and incineration facilities, iron and steel, cement and paper industries	7 Waste plastic, paper and home appliance, steel, blast furnace gas, metal, sludge
Dong et al. (2017)	Liuzhou, China	7 Iron and steel making, cement, carbonate, ammonia and fertilizer production, power generation, communities	8 Steam, slag, waste steel, scrap tire, waste plastic, ammonium sulfate, coal ash, biomass
Kerdlap et al. (2019)	Singapore	5 Farm, hotel & restaurant, biodiesel plant, food waste digester, transport service	6 Food waste, waste cooking oil, food, animal feed and fertilizer, biodiesel
Kim et al. (2018)	Ulsan, Korea	5 Industries (2), urban areas (3)	1 Focused on waste heat exchanges
Fang et al. (2017)	Guiyang, China	10 Iron, aluminum, cement and coal industries, phosphorus and coal chemical industries, power plant, combined heat & power plant, urban areas, green house	8 Waste heat, slag, coal products, coal, steam, power, hot water, municipal waste

2.2. *Urban industrial symbiosis assessment*

2.2.1. *Structural assessment with ecological network analysis*

The use of biological tools to assess human-related networks relies on the industrial ecology concept, which was inspired by the interactions found in natural ecosystems (Erkman, 1997). The ENA method was initially developed for biological systems by Ulanowicz (2004, 2001, 1986), based on Rutledge et al. (1976). This method includes various metrics allowing to assess various network characteristics. Among them, the flow-based metrics allow to assess the flow organization (Layton, 2014), providing insights into the system balance and thus its ability to develop and to maintain itself when confronted to external perturbations (Kharrazi et al., 2013).

The ENA flow-based analysis relies on the calculation of two metrics: one that capture the constraint degree in the network (efficiency) and one that estimates the degree of freedom (redundancy) (Ulanowicz, 2004). A network with a high efficiency is more constraint than a network with a high redundancy. Under ENA perspective, efficient networks present few links or disbalanced links; redundant networks present more links or more evenly balanced links (Fath and Scharler, 2019). The robustness metric allows to put the opposing network's trends (efficiency and redundancy) in one single metric, easing the ENA results interpretation (Fath, 2015) and providing insights on the system's capacity to maintain itself over time (Kharrazi et al., 2013).

To provide a visual representation of the studied network balance, robustness is often plotted to the degree of order (the ratio between the two network's trends), forming the fitness curve. According to several ecological studies, the robustness of natural ecosystems falls within a range of values called the “Window of Vitality” (Fath and Scharler, 2019; Ulanowicz et al., 2008). This range of values is defined by a degree of order that lies between 0.30 and 0.58 (Layton, 2014; Souza et al., 2019; Ulanowicz, 2009). The position of a network on the fitness curve also provides information on its properties, namely if the network is more redundant (left side of the curve) or more efficient (right side) (Fath and Scharler, 2019).

Even though the ENA method has been initially designed for the study of biological ecosystems, it has since been applied to human-related systems and especially UIS (Fang and Chen, 2015; Hairston and Layton, 2021; Morris et al., 2020). The studies mobilizing ENA flow-based metrics fall into two main categories: descriptive and design-oriented. The first are focused on analyzing networks and comparing them to natural ecosystem to understand how they differ and/or resemble; the second use ENA metrics, and especially the robustness, to design networks that are intended to be more effective in absorbing perturbations and maintaining their function. In both cases, the fitness curve and the Window of Vitality are used as a reference point to evaluate the structural performance of the studied networks (Morris et al., 2020). An overview of representative ENA studies is presented in Table 2, focusing on the metrics and how they are interpreted.

2.2.2. *Regional assessment*

Studies dedicated to the consequences of the creation of a symbiosis in a region are rare (Virtanen et al., 2019). Ogé (2021) developed a

Table 2
Overview of ecological network analysis applied to human-related networks using flow-based metrics.

Reference	Network (flow)	Type of study	Metric used	Associated interpretation
Morris et al. (2020)	UIS (material, energy and water) & natural (energy)	Descriptive	Average mutual information Robustness	For both metrics, UIS networks had greater range of values than natural networks Networks displayed on fitness curve to show that the position is driven by the type of flow considered and they are not condensed in the Window of Vitality
Panyam et al. (2019)	Power grid (energy)	Design (by optimization)	Robustness (as the objective function)	Optimized networks closer to the Window of Vitality than the original networks
Fang and Chen (2015)	District (water)	Descriptive, over time	Average mutual information and residual diversity Robustness	Evolution of network concentration and flow distribution (more or less even) Evolution of the position on the fitness curve implying that the studied network is more redundant
Kharrazi et al. (2013)	Economic trade (money)	Descriptive, over time	Average mutual information and residual diversity Robustness	Evolution and trend of the metrics as the reflection of the fluctuation on the global economic trade network Position of economic networks regarding natural ones, showing that human networks are less robust

thesis to assess the impacts of synergy integration on a region's operation. Among the set of metrics proposed by the author, the ones related to regional autonomy are of particular interest for this study as they allow gauging the state of a region with regard to its relationship with its surroundings. The metrics of interest presented by Ogé (2021) are based circular economy studies, even though a circularity analysis at the regional level is rare (Virtanen et al., 2019). Despite this, the studies' results showed that the circularity metrics can bring interesting insights. For example, at the supply chain scale, Brändström and Eriksson (2022) showed that circular economy strategies allowed input and output flow reduction. Guo et al. (2017) studied similar strategies at the urban scale and showed that the performance varied depending on the level of technological development in the region considered. It has also been showed that the circularity performance at a given scale does not necessarily translate at a larger scale (Wang et al., 2018a), revealing the need for an assessment at various levels to ensure the positive impacts of synergies, as also noted by Virtanen et al. (2019).

2.2.3. *Environmental assessment*

The environmental assessment of UIS is mainly carried with material flow analysis and LCA, which revealed that such systems allow benefits in terms of resource consumption, emissions, and waste disposal (Neves et al., 2020). UIS environmental benefits are often measured by scenario analysis, in which symbiosis are created and assessed compared to a linear or less symbiotic situation. For example, Ohnishi et al. (2017) compared a non-symbiotic situation and a symbiotic situation considering only material synergies and showed a carbon footprint reduction of about 14 %. Dong et al. (2017) developed scenarios consisting in reusing material waste, biomass conversion to energy and carbon capture. By a life cycle approach, they evaluated CO_2 mitigation effects and showed that the synergies allowed CO_2 emission reduction, especially the ones with biomass use and carbon capture. Interestingly, the authors also note that over the life cycle, synergies can contribute to CO_2 increase because of cross-boundary transportation, showing that the overall benefits can results in local impact increase. Geng et al. (2010) also developed an LCA approach to evaluate the CO_2 emissions from synergies focused on municipal waste management, including material recycling and biomass to energy (biogas plant). All the symbiosis scenarios showed a CO_2 reduction compared the reference scenario (waste incineration) and similarly to Dong et al. (2017), the authors showed an increase in transportation CO_2 emissions in the symbiosis scenarios.

The LCA approach has also been proven useful to assess various environmental impact categories, in addition to CO_2 emissions. Authors assessed, among others, impact on climate change, acidification, eutrophication, depletion of abiotic resources or human toxicity (Martin, 2018; Martin et al., 2019). In studies that evaluated symbiosis scenarios with municipal compost used in industrial organizations (Martin, 2018) or biofertilizer from the regional biogas plant and by-product from local industry use (Martin et al., 2019), authors showed that extended industrial symbiosis allowed impact reduction for all the impact categories assessed, with major effect on climate change.

3. Methodology

3.1. *Multidimensional assessment*

The proposed assessment framework includes three dimensions: structural, regional and environmental, which are described in the following sections. To perform the study, tools identified in the literature were used to assess each dimension. The ENA and more specifically the robustness metric was used to gauge the structural performance of the scenarios in terms of network configuration, encompassing the way actors are connected both at a topological level and in regard to the flow magnitude. Circular economy metrics were chosen for regional performance, assessing both the dependence on primary resources (circularity index) and the external supply (dependence index). Finally, the LCA approach was used to perform the environmental analysis to be able to encompass different impacts.

Looking at the networks through these various lenses aimed to offer a comprehensive view of the symbiosis performance. This assessment framework was applied to scenarios, based on a real industrial symbiosis case, that represent the progressive inclusion of an industrial symbiosis in a larger system to build a regional symbiosis. For the three dimensions assessed, the scenarios were ranked to both compare them with each other and to analyze the variations and/or similarities between the dimensions. Sections 3.1.1, 3.1.2 and 3.1.3 provide the metrics definition for structural, regional and environmental dimension, respectively. Then, Section 3.2 describe the illustrative case studied, with information on scenario building and ranking (Sections 3.2.1 and 3.2.2) and details on data sources (Section 3.2.3).

3.1.1. *Structural assessment*

The metrics of interest in this study are flow-based metrics. They provide insights into system maturity and the ability of the system to evolve when facing perturbations (Kharrazi et al., 2013; Layton, 2014; Ulanowicz, 2004). Among the flow-based metrics, the robustness is used in network design (Chatterjee and Layton, 2020; Dave and Layton, 2020; Layton et al., 2016). It measures the balance between the two core metrics of a network ability to maintain itself: the efficiency (constraints) and the redundancy (freedom) (Kharrazi et al., 2013).

Regional systems can be studied from a network perspective by abstracting them as graphs with nodes and edges that represent entities (actors) and interactions (exchanges), respectively. The ENA flow-based metrics are calculated using the flow matrix T, in which t_{ij} represents the flow t moving from node i to node j. To compute the metrics, flows are expressed in an energy unit (in this study, Joules). The metrics computed are summarized in Table 3. For an in-depth explanation of these equations and their foundations, please refer to Ulanowicz (2009, 2001) and Ulanowicz et al. (2008). As the aim of the structural evaluation is to evaluate the network configuration of the region itself, only the internal relations are considered in the ENA metrics calculation (Ulanowicz, 2004; Ulanowicz and Norden, 1990). Thus, the analysis focuses on the evolution of the symbiosis network to better describe how the internal changes affect the structural performance. The two other dimensions (regional and environmental) reconnect the symbiosis to its external environment as they consider input and output flows that either generate dependency (regional dimension) or environmental impact (environmental dimension). The study is therefore able to put metrics that give various level of information in perspective.

The Average Mutual Information (AMI) metric measures the constraints in the network, representing the efficiency property, or the level

Table 3
ENA metrics used for the structural assessment. T = flow matrix; t_{ij} = flow going from i to j expressed in energetic unit (Joules).

Metric	Formula[1]	Name & meaning	Reference
AMI	$\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{t_{ij}}{T_{..}}log_2\left(\frac{t_{ij}T_{..}}{t_{i.}t_{.j}}\right)$	**Average mutual information** Order and organization of the network	Kharrazi et al., 2013; Ulanowicz, 2004
H	$-\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{t_{ij}}{T_{..}}log_2\left(\frac{t_{ij}}{T_{..}}\right)$	**Shannon index** Remaining redundancy	Chatterjee and Layton, 2020; Ulanowicz, 2004, Warrington and Layton, 2022
R	$-\frac{AMI}{H}ln\left(\frac{AMI}{H}\right)$ where AMI/H is the degree of order	**Robustness** Ability of the system to persist, trade-off between efficiency and redundancy	Chatterjee and Layton, 2020; Fang and Chen, 2015; Fath and Scharler, 2019

[1] Dot notation refers to summation over the full range of the index.

of organization (Chatterjee and Layton, 2020). The H metric measures the number of connections that can be created (Warrington and Layton, 2022), reflecting the possibility for the network to develop its redundancy property. The ratio of AMI and H is the degree of order: when the degree of order is 0, the network is overly redundant; when the degree of order is 1, the network is overly efficient. Together, the ENA flow-based metrics allow computing the robustness metric R, which represents the balance between the two networks' properties (Kharrazi et al., 2013): when the degree of order is 0 or 1, the robustness is 0 (or close to 0), which means unbalanced networks.

3.1.2. Regional assessment

The regional performance of the symbiosis was assessed based on region-specific circularity indicators. These metrics qualify scenarios according to (i) the capacity to relocate the resource origins (circularity) and (ii) the region relation with an enlarged environment (dependence), in accordance with one of the regional symbiosis purposes, which is to relocate resource flows (Korhonen, 2001).

The metrics chosen in this study were built by the authors and based on the work of Ogé (2021), who identified specific metrics to assess territorial autonomy. These metrics allow us to have a snapshot of regional performance in regard to dependence on external resources and the contributions of symbiosis to the evolution of these metrics. The first metric used is the circularity index C_s (Eq. (1)), which is the ratio of secondary flow consumption produced within the UIS system to the total consumed input flows (adapted from Ogé, 2021).

$$C_s = \frac{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij}\right)_s}{\left(\sum_{i=0}^{n}\sum_{j=1}^{n} t_{ij}\right)_s} \tag{1}$$

where *s* is the scenario under study, *n* is the number of actors and t_{ij} is the flow *t* moving from *i* to *j*. The enumeration of the index *i* and *j* begins at 0, where 0 represents the import source, while the other values from 1 to *n* represent actors involved in the symbiosis (e.g., firms). The second metric is the dependency index D_s (Eq. (2)), which quantifies the dependence on imports compared to a reference scenario (adapted from Ogé, 2021).

$$D_s = \frac{\left(\sum_{j=1}^{n} t_{0j}\right)_s}{\left(\sum_{j=1}^{n} t_{0j}\right)_{ref}} \tag{2}$$

where *s* is the scenario under study and *ref* is the reference scenario. For both the circularity and the dependency indices calculation, the flows were expressed in an energy unit (Joules). The results were expressed as percentages.

3.1.3. Environmental assessment

The environmental impact of the regional symbiosis networks was calculated using an LCA approach. The assessment included the impacts of the processes and of transportation between the regional symbiosis entities and/or between the external environment and the regional symbiosis. The indicators chosen for the environmental evaluation are three midpoint impact categories based on the ReCiPe impact assessment method: climate change (GWP), terrestrial acidification (TAP) and freshwater eutrophication (FEP). These impact categories were selected as they are the most common indicators used in LCA studies for industrial symbiosis systems (Liu et al., 2021b; Martin et al., 2014; Røyne et al., 2018). For each category, the total impact was calculated using Eq. (3). This equation was built upon the LCA impacts calculation principles, which state that the total impact of a system is equal to the quantity of each product multiplied by its elementary impact (Margni and Curran, 2012).

$$\text{Impact} = \sum\nolimits_f \left(q_f s_{mf} + t_f s_{tf}\right) \tag{3}$$

Where indices *m* and *t* refer to material and transport, respectively, q_f is the quantity of flow *f* (expressed in a mass or energy unit, depending on the flow considered), t_f is the transport of flow *f* (in mass kilometers) and s_f is the impact score for flow *f* (expressed in quantity of element equivalent per quantity of flow). The results were therefore expressed in quantity of CO_2 equivalent (GWP impact), quantity of P equivalent (TAP impact) and quantity of N equivalent (FEP impact).

3.2. Illustrative case and data

3.2.1. Regional symbiosis scenarios

The regional scenarios were based on a real case study, the Sötenas industrial symbiosis presented in Martin and Harris (2018). This case study was then expanded to integrate hypothetical but realistic regional scenarios. These scenarios were developed to illustrate a growing regional symbiosis: considering the Sötenas industrial symbiosis as a starting point, a regional symbiosis was modeled and enriched by the inclusion of new regional actors. This design process thus reflected a possible regional evolution and allowed us to explore how the multidimensional indicators would evolve, depending on how much the industrial symbiosis is embedded in the regional area.

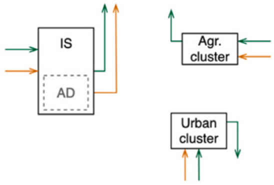
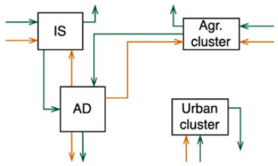
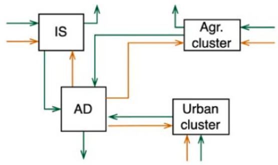
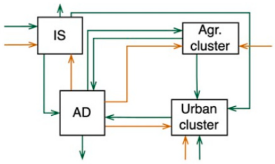
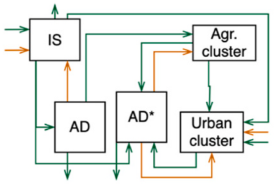
The main actor in the Sötenas industrial symbiosis is a fish processing plant exchanging material and energy flows with an anaerobic digester. The fish processing plant consumes electricity, heat and raw fish and releases fish products. The anaerobic digester consumes the fish waste from the fish plant and generates electricity and heat.

The regional symbiosis scenarios were developed based on existing UIS (among others, see Milan, Malmö and Samsø in Ellen MacArthur Foundation, n.d.). More specifically, agricultural and urban clusters were included, as they are common actors found in documented UIS cases (Morris et al., 2020; Neves et al., 2020). Furthermore, given that the Sötenas symbiosis was built around an anaerobic digester, the choice of the regional actors was guided towards clusters that could have an interest in supplying and/or receiving products from the digester. Consequently, the main flows considered in this study were the ones contributing to the regional symbiosis function, defined by the digester's main output, which is electricity production (Martin and Harris, 2018). Thus, the material flows considered were limited to biowaste and their sources and the energy flows considered were electricity (main product from the anaerobic digester) and heat (co-product).

Based on these considerations as well as on the UIS types identified in the literature review (Section 2.1), four scenarios were built. They are presented in Table 4, where the boxes represent the actors and the arrows represent the exchanges (i.e., synergies) between actors (e.g., a green arrow between the “Agr. cluster” and “AD” actors represents the biowaste flow going from the agricultural cluster to the anaerobic digester, and the orange one represents the electricity and/or heat going from the anaerobic digester to the agricultural cluster). The specific flow types exchanged can be found in Table S1 in the Supplementary Information. In the reference scenario, there is no UIS, each actor operates on its own and the anaerobic digester is dedicated to the industrial actors. The scenario design process considers that the four actor types (industrial symbiosis, anaerobic digester, agricultural cluster and urban cluster) are progressively included in an UIS system (scenarios I to IV). First, loops were modeled on waste-energy exchanges, in which an entity of the network gives waste and receives energy (scenarios I and II). These first two scenarios were built to give insights on how the integration of regional actors can affect the performance of the symbiosis. Then, material flows (fish products, fruits and vegetables, biofertilizer) were considered to enrich the initial regional symbiosis (scenario III). The performance variation can thus be analyzed regarding the inclusion of new flows in the regional symbiosis. Finally, a scenario was added to

Table 4

Regional symbiosis scenarios. Green arrow = material flow; orange arrow = energy flow; REF = reference; AIS = agro-industrial symbiosis; UAIS = urban agro-industrial symbiosis; EMS = energy and material symbiosis; EMSd = EMS distributed; IS = industrial symbiosis; AD = anaerobic digester.

0. REF	I. AIS	II. UAIS
		
Reference No regional symbiosis – all the flows come and go to the external environment; the anaerobic digester (AD) is part of the industrial symbiosis (IS) and supplies it with energy (electricity and heat).	**Energy symbiosis: the agro-industrial system (AIS)** The anaerobic digester (AD) becomes a system entity, supplied by organic waste (fish waste) from the industrial symbiosis (IS) and returning energy (electricity and heat) to it. The agricultural cluster is included in the symbiosis: it supplies the anaerobic digester with organic waste (fruits and vegetables losses) and receives energy (electricity and heat).	**Energy symbiosis: the urban-agro-industrial system (UAIS)** The urban cluster is included: it supplies the anaerobic digester (AD) with organic waste (food waste) and receives energy (electricity and heat).
III. EMS	**IV. EMSd**	
		
Energy & material symbiosis (EMS) The material flows between three entities are included: the urban cluster is supplied by the industrial symbiosis (IS) (fish products) and the agricultural cluster (vegetables and fruits); the agricultural cluster is supplied by the industrial symbiosis (IS) (biofertilizer).	**Energy & material symbiosis - distributed structure (EMSd)** The same synergies occur as in scenario III but the energy production is distributed: an anaerobic digester (AD*) is added, and biomass flows are equally distributed between the two digesters. Each symbiosis entity is supplied by one anaerobic digester.	

reflect the options that a region could have regarding its planning in terms of infrastructure size and flow destination (scenario IV). This scenario allowed to discuss the choice between centralized and distributed structures, which has been identified as a criterion for decision making in regional planning (Fraccascia et al., 2021; Tanguy et al., 2017).

The scenario development followed several methodological choices:

- The industrial symbiosis consumes energy and raw fish and produces fish products and energy (a result of extra production from the anaerobic digester), a choice based on the actual situation in Sötenas;
- The anaerobic digester supplies the industrial symbiosis entities with electricity and heat for all the modeled scenarios (including the reference scenario, representing the actual situation in Sötenas);
- The agricultural cluster consumes energy and fertilizers and produces vegetables and fruits;
- The urban cluster consumes vegetables, fruits and fish products and produces food waste;
- The urban cluster consumes electricity and heat. Heat is considered as the only source for district heating.

As this study intends to position the scenarios relatively to one another rather than interpret their absolute performance, the scenarios were ranked from 1 to 5 for each dimension assessed, with 1 being considered as the best position. The ranking was performed as follows, in which equal ranking was allowed when the scenarios' performance was identical:

- Structural dimension: the ranking was based on the robustness metric. The scenarios were sorted in descending order (rank 1 for the highest robustness).
- Regional dimension: the ranking was based both on the circularity and the dependency metrics. Rank 1 corresponded to the highest circularity performance (sorted in descending order) and the lowest dependency performance (sorted in ascending order).
- Environmental dimension: the ranking was based on the three impact categories assessed. The scenarios were ranked in ascending order (the lower the impact the better).

3.2.2. *Modeling of alternative symbiosis function*

The anaerobic digestion process leads to biogas and biofertilizer production. Biogas can be directly used as an alternative to natural gas or to produce electricity (and heat as a co-product). It can also be upgraded to biomethane, which is used in several sectors, including transportation (Ardolino et al., 2018).

The original anaerobic digester function in Sötenas industrial symbiosis is electricity production, with heat as a co-product (Martin and Harris, 2018). To further explore the regional potential of the industrial symbiosis, an alternative function was modeled in which biomethane production was used as an alternative for fuel (diesel) in transportation. The same scenarios as presented in Table 4 were assessed and compared. Input needs for electricity and heat were replaced by fuel needs. They were determined considering the following assumptions:

- At the industrial symbiosis level, the fuel needs for transportation within the symbiosis are considered;
- For the agricultural cluster, the fuel needs for machinery operation and waste transport are considered;
- For the urban cluster, the fuel needs for trucks (good transport) and buses (public transportation) are considered;
- Once biomethane is produced, it is used by the regional actors involved in the symbiosis.

3.2.3. Data sources

The Sötenas municipality was selected as the study region as it is where the industrial symbiosis is located. The industrial symbiosis flow data were based on Martin and Harris (2018). The input/output flows for the agricultural and urban clusters were based on Sötenas municipality, Västra Götaland county and Sweden data. The two main variables driving most of the flow volume were the number of inhabitants and the agricultural land surface, which were fixed at 9000 and 1439 ha, respectively (Statistics Sweden, n.d.; Swedish Board of Agriculture, 2019). The input/output flows involved in the network are presented in Table S1 with transport data for the reference scenario. The transport distances in the symbiosis scenarios were based on average distances from the industrial symbiosis location to extreme points in Sötenas municipality. The internal flow data were determined by comparing the output quantities to the input needs, ensuring that as much as possible of the input needs were fulfilled by the regional symbiosis.

Data for the environmental assessment were also needed, in particular for the impact scores. These data were obtained from different sources (mainly the Ecoinvent database (version 3.7) but also relevant LCA studies). All the data concerning impact scores are presented in Table S2.

The ENA analysis imposes the use of the same unit for all flows, as they are summed. Thus, all the flows were converted to a common unit, (a unit of energy, Joules). Material flows were converted based on intrinsic energetic values found in the literature. Further details concerning the conversions and the assumptions made are available in Table S3.

4. Results

4.1. Structural, regional and environmental assessment

The numerical results of the regional symbiosis multidimensional assessment are presented in Table 5 (electricity case) and Table 6 (biomethane case), alongside with the scenarios ranking.

The same trends were observed for the two anaerobic digesters function modeled (electricity and biomethane). The ranking was the same for the three dimensions assessed and showed that the performance increased when the number of synergies increased, i.e., when the exchanges intensified (from scenario I to scenario III or IV). Nevertheless, each dimension showed some particularities:

- Structural dimension: this was the dimension with the most significant change between the scenarios in terms of absolute values. In the electricity production case, the biggest gap was observed between scenario I and II while in the biomethane case, it was between II and III. This observation revealed that both adding actors or flows to the symbiosis can have a beneficial impact in term of robustness. However, this result was sensitive to the type of flow considered. Plus, the robustness was higher for scenarios with electricity production, except for scenario IV (0.35 for the biomethane case versus 0.34 for the electricity case).

Table 5

Structural, regional and environmental performance and ranking (electricity). GWP = global warming potential; TAP = terrestrial acidification potential; FEP = freshwater eutrophication potential; REF = reference; AIS = agro-industrial symbiosis; UAIS = urban agro-industrial symbiosis; EMS = energy and material symbiosis; EMSd = EMS distributed.

Metric [unit]	R. REF	I. AIS	II. UAIS	III. EMS	IV. EMSd
Degree of order (AMI/H) [n.d]	–	0.99	0.76	0.64	0.53
Robustness (R) [n.d]	–	0.01	0.21	0.28	0.34
Structural ranking	–	***4***	***3***	***2***	***1***
Circularity index (C) [%]	0.12	0.12	0.13	0.13	0.13
Dependency index (D) [%]	100	100	99.99	99.99	99.99
Regional ranking	***4***	***3***	***2***	***1***	***1***
GWP [kg CO_2eq]	4.72E+8	4.72E+8	4.72E+8	4.72E+8	4.72E+8
TAP [kg SO_2eq]	1.31E+7	1.31E+7	1.31E+7	1.31E+7	1.31E+7
FEP [kg Peq]	2.95E+5	2.95E+5	2.95E+5	2.95E+5	2.95E+5
Environmental ranking	***5***	***4***	***3***	***1***	***2***

Table 6

Structural, regional and environmental performance and ranking (biomethane). GWP = global warming potential; TAP = terrestrial acidification potential; FEP = freshwater eutrophication potential; REF = reference; AIS = agro-industrial symbiosis; UAIS = urban agro-industrial symbiosis; EMS = energy and material symbiosis; EMSd = EMS distributed.

Metric [unit]	R. REF	I. AIS	II. UAIS	III. EMS	IV. EMSd
Degree of order (AMI/H) [n.d]	–	1.00	0.89	0.72	0.48
Robustness (R) [n.d]	–	0.00	0.11	0.24	0.35
Structural ranking	–	***4***	***3***	***2***	***1***
Circularity index (C) [%]	23.69	24.12	35.35	36.26	36.26
Dependency index (D) [%]	100.00	99.44	84.74	83.68	83.68
Regional ranking	***4***	***3***	***2***	***1***	***1***
GWP [kg CO_2eq]	1.20E+8	1.20E+8	1.19E+8	1.19E+8	1.19E+8
TAP [kg SO_2eq]	2.21E+6	2.21E+6	2.20E+6	2.20E+6	2.20E+6
FEP [kg Peq]	4.15E+4	4.15E+4	4.15E+4	4.15E+4	4.15E+4
Environmental ranking	***5***	***4***	***3***	***1***	***2***

- Regional dimension: in contrast with the previous dimension, the regional performance of scenarios III and IV was exactly the same, as it involved the exact same flow quantities, indicating that only the structural and environmental performances were impacted. The biomethane production allowed an increase of the regional metrics for all the scenarios, with the circularity index raising from less than 1 % to approximately 30 % and the dependency index going from almost 100 % to under 90 %.
- Environmental dimension: from this perspective, biomethane production performed better than electricity production, as the impact values were lower. The impact values of the five scenarios were close to each other, regardless of the case and the impact category. In both energetic cases, the symbiosis allowed a small improvement (lower impact) compared to the reference scenario, even if the benefits were greater for biomethane production, in particular for GWP and TAP (0.7 % and 0.3 % decreases, respectively, considering scenario III). Scenario III performed better than scenario IV because of transport: there was more truck travel to transport waste in the distributed scenario (scenario IV), leading to an increase in impacts. The shift in the fuel source (biomethane case) did not change this observation.

While the robustness results were only due to the network configuration, the regional and environmental results can be explained both by the network configuration and the flow types. Indeed, the configuration influenced the needs for outside supplying, but in various intensity depending on the flow considered. Thus, a flow type analysis was carried out, to assess the importance of flow type in regional and environmental performance.

4.2. Flow analysis

To better understand the regional and environmental results, a closer look was taken by separately assessing the energy and material flows. In the electricity case, the circularity index of scenarios III and IV (in which both energy and material synergies are involved) was low because the energy imports were still high, despite the share of material input covered by the symbiosis (12.6 %). The circularity index was higher for material (approximately 27 %) than for energy flows (approximately 0.04 %), while the dependency index was high for both flow types (close to 100 %). From the environmental perspective, energy flows were responsible for the larger impacts for all the impact categories, while material flows accounted for 33 %, 20 % and 16 % of GWP, TAP and FEP, respectively. The metrics for the material flows in the biomethane case were the same as in the electricity case, as the flows were unchanged. Thus, the improvement in the performance came from the energy flows. As biomethane production was able to supply the entire fuel needs for the industrial symbiosis, agricultural and urban clusters, energy flow circularity was improved, and dependency on external suppliers was simultaneously reduced. From the environmental perspective, the impacts of energy flows were lower than those of material flows. The figures supporting the percentages cited in this section can be found in Tables S4 and S5.

4.3. Multidimensional analysis based on the window of vitality

Fig. 1 displays the structural results plotted on the fitness curve, along with the regional and environmental rankings. Note that the marker for scenario 0 is displayed for reference purposes only and does not indicate a redundant structure, as it is a non-symbiotic scenario.

The marker positions for all of the scenarios were located on the right side of the curve, showing that networks were more efficient than redundant (Fath and Scharler, 2019). Except for scenario IV, the UIS networks were outside the Window of Vitality, which is in line with findings from other studies (Morris et al., 2020; Kharrazi et al., 2013). The scenarios position on the curve also revealed that the distributed organization allowed a more evenly balanced network. Only scenario IV was located in the Window of Vitality for both the electricity and biomethane cases, the latter of which was the highest. In contrast, for the other scenarios, the electricity scenarios' robustness was higher than the biomethane one, suggesting that not only the actors' relations but also the intensity of the flows influenced the robustness metric, as suggested by other studies (Morris, 2020; Warrington and Layton, 2022). Considering the regional and environmental performances, scenario III was in the first position for both dimensions. Nevertheless, it must be noted that the ranking of the environmental dimension is to be considered in regard to the values displayed in Tables 5 and 6, which are close to one another.

5. Discussion

5.1. Urban-industrial symbiosis multidimensional assessment

This study focused on the multidimensional assessment (structural, regional and environmental) of a growing regional symbiosis between various actors (the industrial symbiosis itself, the agricultural cluster and the urban cluster) in two energy production cases (electricity and biomethane). Overall, the results showed a correlation between expanding the network and regional, structural and environmental performances. Dong et al. (2022) found similar results for an industrial symbiosis evaluation focused on energy exchanges, and Barrau and Glaus (2023) showed that increasing the number of exchanges improved the environmental performance of an industrial symbiosis. Nevertheless, these results do not mean that this positive correlation between regional symbiosis performance and size or complexity is systematic. For example, Barrau and Glaus (2023) showed mixed results in regard to the correlation between network complexity and ENA robustness in the case of an IS. Kim et al. (2018) also showed, when considering energy synergies, that benefits in terms of CO_2 reduction are not strictly proportional to the expansion of the symbiosis boundaries. Those mixed results shed light on the question regarding, on the one hand, the relevant scale to assess the benefits of a symbiosis and, on the other hand, where to set boundaries when developing synergies (Chen et al., 2012; Marcinkowski, 2019). Indeed, regional systems are open, and the flow circulation in a globalized economy questions what could be considered a “territory” (Cerceau et al., 2018). It could thus imply that the relevant scale to which synergies develop should be a dynamic process, as the benefits can vary depending on the regional characteristics, assessed flows and actors considered.

The results also showed that the energy and material flows carry different environmental impact intensities and contribute in different proportions to the regional performance (circularity and dependence indexes). These different flow types can be seen as layers of the same network (Valenzuela-Venegas et al., 2018). The electricity case showed that the regional benefits brought by the material layer are not necessarily transferred to the energy layer. Indeed, material circularity does not have significant effects on regional or environmental metrics of the energy layer, thus questioning the relevance of the outcome product. In contrast, the biomethane case showed that the regional and environmental benefits were mainly supported by the energy layer. This comparative analysis revealed that the benefit gap between the material

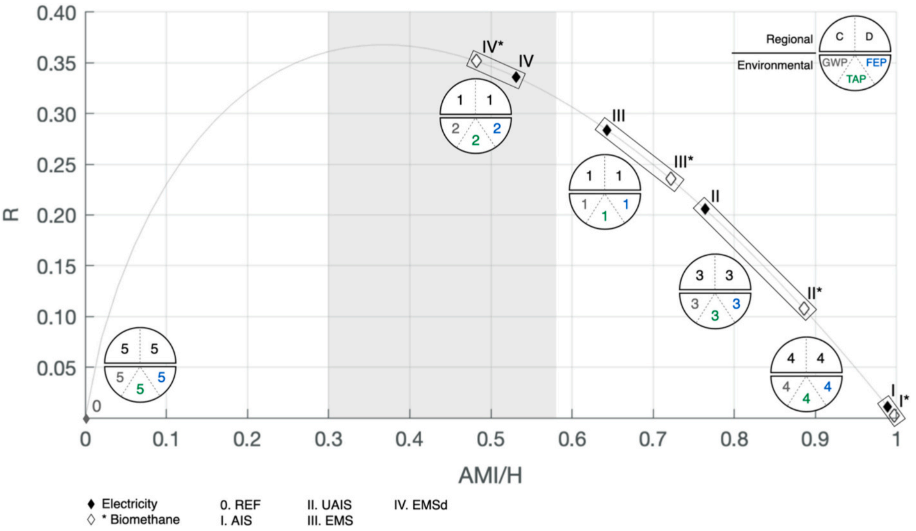


Fig. 1. Fitness curve displaying the structural performance (R) for each scenario coupled with regional and environmental ranking. Gray zone = Window of Vitality; REF = reference; AIS = agro-industrial symbiosis; UAIS = urban agro-industrial symbiosis; EMS = energy and material symbiosis; EMSd = EMS distributed; C = circularity; D = dependency; GWP = global warming potential; TAP = terrestrial acidification potential; FEP = freshwater eutrophication potential.

and energy flows can vary depending on the energetic case, highlighting the importance of regional planning and the choice of appropriate processes and their output benefits. This finding was in line with the work of Laurent (2015), who showed that technology choices should be based on the needs and main functions of a region. Evaluating the different layers of flows in a symbiosis showed that a "trans-layer" approach should be followed when considering its benefits (in whatever dimension). Such a systemic perspective allows to assess benefits from the loops in the energy layer based on their contribution to the material layer, even though they may seem pointless on their own. It also appears necessary as energy loop creation depends on material flows, leading to a dependence between the network layers. This conclusion advocates for a comprehensive approach in regard to the technology choices implemented in a region, which also facilitates cooperation among regional actors (Vanhamäki et al., 2020).

The results also showed that, in general, the three assessed performances were improved with industrial symbiosis expansion in the region. The absence of a best scenario for all assessed dimensions indicates that trade-offs could and should be found when planning industrial symbioses at the regional scale, which is in line with the findings of other studies. Despite a different context (Italy), Fraccascia et al. (2021) showed that there is a compromise to make between economic and structural dimensions in the design of biomethane supply chain as the scenarios with the best economic performance were less resilient. Similar to the present study, Souza et al. (2019) mobilized ENA and environmental assessment in a supply chain context and showed that there is no correlation between the two dimensions. Moreover, the results highlight the relevance of multidimensional analysis in regard to complex systems, which allows us to consider systems that can underperform on a given dimension but give overall greater benefits in the long term for a majority of other indicators. This concept echoes those discovered in the natural world, such as suboptimality (Hamant, 2022). Hamant (2022) describes how some complex natural systems, such as the human body, compromise their performance, e.g., reaching the body temperature that optimizes enzyme activity, to increase their robustness over long time periods. The author thus illustrates the intrinsic duality between optimal performance and robustness, a concept addressed by other works in sustainability research, which investigate the balance between efficiency and resilience objectives for sustainable infrastructure (Markolf et al., 2022). In the specific case of industrial symbiosis, environmental performance, via environmental impact minimization, is currently the primary focus of regional planners, in part to address the climate objectives set by international and national regulations. However, examples found in natural systems and ENA research suggest that the survival of complex systems and their integration within their environment rely less on environmental performance optimization than on their ability to organize in a network. An alternative approach to regional planning of industrial symbioses could thus comprise reaching the window of vitality and then adjusting the processes to reduce their environmental impact. For example, in this study, scenario IV could be considered because of its high structural performance but with a shift in the transportation mode to increase its environmental performance.

5.2. Limitations and further research

These results are valid within the scope of the study, which covers only a fraction of the flows involved in a regional metabolism, i.e. biowaste used to generate biogas. Future research could thus work at binding the proposed assessment framework with tools such as material flow analysis or territorial metabolism, which are relevant to assess all the resource flows of a region (Athanassiadis et al., 2016). Future work could also integrate a dynamic assessment to consider the flows variability occurring monthly, weekly or daily (Valenzuela-Venegas et al., 2018). In addition, the scenario development included the integration of flows and actors, which both could explain the performances improvement. To address this limit, it could be necessary to investigate more precisely the influence of actors and flows separately. The environmental dimension had been investigated with three impact categories but enriching the study with other impact categories (resources use in particular) could bring more nuanced conclusions. Finally, this work was focused on a given scale, which was a methodological choice, but it could also be relevant to situate the system performance in regard to the performance of a larger region, as done by Liu et al. (2021a).

Despite these considerations, this study can help guide policymakers on the regional planning of industrial symbiosis and, more especially, on the trade-offs between macrolevel performance metrics. Indeed, the general findings of this paper advocate for a more holistic evaluation that considers a systemic approach when assessing the sustainability of regional systems. Applying the proposed approach on a UIS case such as Kalundborg could enhance the understanding of the success of the symbiosis as it could revealed how the material exchanges support the energetic synergies, or how the network facilitates the regional autonomy. Given the various changes that occurred in this network, the proposed approach could also help to drive further modifications to ensure that useful relations are not jeopardized. It also pleads for network topology to be as valued as technology choices for enhancing comprehensive sustainability. In practice, the development of synergies considered a priori as beneficial should be evaluated with a multidimensional approach. This method would allow us to better understand the implications of some actions, such as circulating materials to produce energy, which may not bring direct benefits but can contribute to overall system improvement.

6. Conclusion

The present study intended to propose a multidimensional framework for the assessment of regional symbiosis considering structural, regional and environmental dimensions. The framework was applied to scenarios based on an existing industrial symbiosis (Sötenas, Sweden) which had been hypothetically expanded to include regional actors (agricultural and urban clusters) and be placed in two energetic cases (electricity and biomethane production). The three dimensions were assessed using respectively (i) ENA flow-based metrics and especially robustness which account for network ability to persist; (ii) circularity and dependency metrics which account for the relation of the symbiotic system with its external providers; and (iii) LCA approach to assess the environmental consequences of the synergies. Accordingly, the aim of this research was to gauge the effects of synergies on the assessed dimensions and provide insights into the relevance of industrial symbiosis integration in regional planning.

The results showed that the industrial symbiosis integration into a broader synergetic system was a lever to improve the robustness, the circularity and the environmental impact of the system. The study emphasized the usefulness of a parallel analysis of the various types of flow that are exchanged in the network, as the general benefit could come from flows that were not beneficial themselves. In general, the results advocated for a trade-off between the dimensions assessed, as they were not affected in the same way depending on the scenarios. Indeed, the environmental dimension was lowly affected by the scenario changes, but they provided a wider effect on regional metrics. The change in energetic production (electricity vs biomethane) did not bring significant results differences in the scenarios ranking. Nevertheless, it showed that, for the region under study, it could be more beneficial to produce biomethane, especially when looking at regional metrics. More generally, this study showed that the structural metrics followed a different trend than the regional and environmental metrics, revealing the complementary views that were brought by the multidimensional analysis.

Despite the case specific results, this study allowed to have a look on how a multidimensional approach could help design more balanced regional planning, by highlighting the complexity and various parameters that could be embedded in regional sustainability. Future work could be focused on binding the proposed framework with other methods to help fill the present gaps. It could also include a dynamic regional analysis which seems relevant to implementing a successful regional circular economy.

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CRediT authorship contribution statement

Enora Barrau: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Audrey Tanguy:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mathias Glaus:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.07.015.

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