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Structural and Environmental Performance of Evolving Industrial Symbiosis: A Multidimensional Analysis

Enora Barrau * and Mathias Glaus

Station Expérimentale des Procédés Pilotes en Environnement (STEPPE-ÉTS), Department of Civil Engineering, École de Technologie Supérieure, 1100 Notre-Dame St W, Montreal, QC H3C1K3, Canada
* Correspondence: enora.barrau.1@ens.etsmtl.ca

Abstract: Industrial symbiosis (IS) involves networks of organizations collaborating through flow exchanges. Scientific research has shown that such systems are able to provide benefits at the environmental level. Structural organization and stability were also studied, as they are linked to resilience (maintenance of activity over time), especially with ecological network analysis (ENA), which considers several dimensions in the assessment of a network organization. Studies combining ENA and environmental assessment are lacking in the literature; therefore, the links between the two dimensions are not well documented. The intention of this study was to fill this gap by analyzing structural and environmental performance simultaneously using ENA and a life-cycle-analysis-based approach focusing on the structural topology of IS. The results show that the two dimensions do not strictly influence each other. Structural performance was found to vary depending on the network structure topology, whereas environmental performance was influenced by the network complexity. To ensure the continuation of IS benefits, the two dimensions should be considered in the decision-making process in IS planification, even if they are independent evaluation criteria. Tradeoffs should be based on IS development possibilities and territorial needs.

Keywords: industrial ecology; symbiosis network; ecological network analysis; robustness; environmental assessment

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1. Introduction

Industrial symbiosis (IS) is among the strategies that private and public actors can implement to contribute to a more circular economy [1]. IS is defined as a network of diverse organizations collaborating through flow exchanges or asset sharing to reduce costs and decrease their environmental impact [2,3]. Therefore, IS networks are diverse in terms of the actors involved (industries, facilities, etc.) and the type of exchanged flows (materials, energy, water, etc.). They also differ in their structural topology, which was studied in [4] based on existing IS networks. IS systems have drawn increasing attention in the scientific community [5], with the aim of understanding the conditions of their emergence and success [6–8].

The performance of IS systems is multidimensional, i.e., their success can be assessed through several criteria. One of the most studied criteria is the environmental benefit provided by IS systems, which is the core argument for developing such networks in industrial ecology. Various methods have been proposed, the most common of which is life cycle analysis (LCA), followed by material flow, energy and exergy analysis [2]. The main findings of environmental studies have been that the reuse of waste or byproducts of one industry by another can reduce environmental impacts in terms of energy and water consumption, air emissions and virgin material use [9–12].

Another important criterion is the network's structure, which is important to assess network stability when facing perturbations. The main method used to perform such analyses is social network analysis [2], but the stakeholder value network approach, food web analysis and ecological network analysis are also mobilized (for details on the different methodologies, see [13]). The ecological network analysis (ENA) method developed by Ulanowicz and colleagues [14,15] has the advantage of assessing a system in multiple dimensions, accounting for the complexity of any human–environmental system [16]. Performing structural analyses provides information on network vulnerability [17–19], the current relationship type [20,21] and resilience [22,23], which are conditions of network stability.

Despite the extensive literature assessing the multiple dimensions of IS performance, few papers have explored both the structure and environmental performance. Case studies have been presented [23,24] in which structural assessment was performed with ENA indicators, but environmental study was limited to CO_2 emissions. Recently, researchers [25] proposed a framework to assess the structure, as well as environmental and economic performance of an evolving IS network in Kawasaki eco-town (Japan). Environmental dimensions were more developed (water and air pollutant emissions and waste generation), but they also considered structural metrics, with a focus on the number of network connections, which provides a less broad assessment than ENA metrics.

To the best of our knowledge, no study has been conducted that approaches environmental evaluation with respect to the network structural topology. Consequently, the aim of this research is to evaluate the possible link between the structural and environmental aspects of IS. Secondly, in this study, we examined the behavior of structural and environmental metrics based on the structural alternatives that exist for IS deployment, which made it possible to identify network configurations that provide conditions for both network continuation and environmental benefits.

In the remainder of this paper, we present a literature review focused on performance assessment of IS (Section 2), the methodology (Section 3) the results (Section 4) and discussion (Section 5), ending with concluding remarks (Section 6).

2. Literature Review

2.1. Structural Performance Assessment

Indicators of structural performance are based on network analysis initially mobilized by ecologists. This comes from the biomimetic inspiration of IS, which was conceptualized as a way for industry to imitate natural ecosystems in order to reduce their impact on their surrounding environment [26]. To perform such analysis, the industrial network needs to be abstracted as a graph, in which nodes and links represent entities and exchanges, respectively [13,16].

ENA metrics are used to assess the sustainability of the system under study, regardless of its nature (e.g., biological, urban or industrial) [16]. When applied to human systems, ENA is used to assess a network structure in two dimensions: the type of relationship between the entities and the flow organization [27]. The first, assessed with organizational metrics such as connectance, cyclicity or utility [20,21,27], provides information such as how the network is organized and the role of an entity. The second, assessed using flow-based metrics [27] such as ascendency and overhead, provides insights into the system balance, maturity and capacity to develop [27,28]. Theses metrics assess two contradictory forces that are at stake in natural ecosystems [29]: efficiency, which quantifies constraints; and redundancy, which quantifies freedom. The balance between these forces enables networks to simultaneously guarantee an efficient transfer of the medium and maintain the possibility of creating new pathways [29,30]. The robustness metric measures this balance and is therefore often used in network design [31–33], as it has been considered a measure of resilience [23,34], i.e., the system's ability to maintain itself over time.

Past work using ENA flow-based metrics has demonstrated that human-related systems adopting food-web characteristics exhibited improved performance [35]. For example, a network optimization process based on ENA objectives improved the robustness of newly designed water [33] and power grid [36] networks. To further analyze the performance of the studied networks, authors often use the fitness curve [29], plotting the robustness against a ratio called the degree of order. According to ecological studies, the robustness of natural ecosystems falls within a range of values called the 'window of vitality' (WoV) [15,37]. Industrial systems are recognized to be globally more efficient than natural systems when energy or trade networks are more redundant [31,34]. In both cases, the result is diminished robustness compared to natural ecosystems. Moreover, ENA flow-based metrics are acknowledged to assess the impact of one individual change across the overall network, as well as being a useful tool when used in combination with other metrics to provide additional insights for network assessment [35].

2.2. Environmental Performance Assessment

The literature revealed that IS implementation provides benefits in environmental terms. This was assessed by flow analysis, measuring the tendencies of inputs and outputs. Results have shown that IS is associated with a reduction in resource consumption, for example, water [9] or energy [38] use, as well as waste flow [10] and pollutant emissions [39]. Economic benefits for companies involved in IS were also noted [9,10,39].

The literature is rich in LCA IS assessment studies, which allow for a more global view of the environmental dimension. The impact categories mainly used for LCA are greenhouse gas emissions, acidification potential and eutrophication potential [12,40–42]. In addition to these categories, some other indicators have also been introduced, such as energy use, ozone depletion, resource scarcity and toxicity [43–46]. Studies have demonstrated global benefits when implementing IS compared to a non-symbiotic scenario [47]. LCA studies had been undertaken on very diverse IS networks. Implementation of IS in the forestry industry showed benefits in term of climate change, acidification, eutrophication, tropospheric ozone and particulate matter impact categories [11]. IS in a chemical industry cluster [48] showed improvement in terms of climate change, acidification, eutrophication and primary energy use categories, with energy and material substitutions being responsible for the majority of the benefits. Soil production through IS has also been studied and has revealed benefits for the climate change, eutrophication, acidification and abiotic resource depletion impact categories [45], both at the product and company scale.

Despite those global benefits, it should be noted that IS can also cause negative effects. Increases in material use [10] or in pollutant emissions [9,39] have been reported, as well as a negative impact on eutrophication [49]. These observations highlight the fact that benefits can vary depending on the case under study and the need for tradeoffs in decision making.

2.3. Multidimensional Analysis

A small number of papers offer a multidimensional approach to IS assessment. Using the ENA robustness indicator, the authors of [24] characterized the carbon intensity of Chinese territories to develop decarbonization strategies with respect to the system's robustness; the higher the robustness, the higher the concentration of carbon flows. Still, with ENA, it was shown by the authors of [23] that robustness can be compromised when looking for the minimal environmental impact in a sugar beet supply chain; the best robustness results were obtained for scenarios in which neither profit nor CO_2 emissions were maximized/minimized.

To the best of our knowledge, only one study has assessed IS using a structural, environmental and economic approach [25]. Structural performance was assessed with network analysis indicators (connectivity), environmental performance was based on water and air pollutant emissions, and waste generation and the economic aspect were measured in terms of benefit. They proposed a dynamic evaluation of the Kawasaki IS network to highlight the contributing role of each synergy during IS development and concluded that the more the IS is developed, the greater the benefits in terms of energy savings.

In summary, structural IS assessment with flow-based metrics can provide useful insights in terms of network organization performance. At the environmental level, the LCA approach allows for evaluation of different impact categories, which provides a broader image of the environmental impact than CO_2 emissions or resource savings alone. Studies combining different assessment categories mobilize either partial structural indicators or limited environmental impacts. The intention of this study was to fill this gap by proposing a methodology that combines structural and environmental analyses to propose a multidimensional assessment of an IS network. We focused on the network topology alternatives and the associated environmental impact to evaluate whether the structure type can be considered a criterion for environmental performance. The resultant analysis takes a closer look at the robustness metric, as it can be considered an evaluation of resilience, a property pursued by those setting up IS networks.

3. Methods

The methodology mobilized ENA flow-based metrics for structural assessment to gauge the system's sustainability. Those metrics were computed based on exchange data from the studied IS networks. Environmental assessment was then carried out with an LCA approach to gauge the impacts of IS. Characterization factor selection was based on the relevant literature and the Ecoinvent database, following common practice in the LCA research field. These assessments were carried for scenarios built from three network structural topologies identified by the authors of [4], applied to a real case documented in the literature (the IS of Sötenas, Sweden) [50].

3.1. Structural Analysis

The ENA metrics of interest were flow-based metrics, which are calculated using the flow matrix (T), where t_{ij} represents the flow (t) moving from i to j. In this study, the analysis was focused on internal exchanges, as it is the IS structure itself, more than the links with the surrounding environment, that is the subject of interest [51]. In the analysis of food-web networks, ecologists consider energy as the flow running between entities, allowing for the amalgamation of different energy sources (it is considered the same, irrespective of the energy source). However, IS networks are composed of diverse types of flows, which are often non-interchangeable. Therefore, 3D ENA equations were used in this study to consider a third dimension in the calculation, namely the different medium types. The three dimensions were the donor entities (i), receiver entities (j) and medium type (k). Flows were noted as t_{ijk}. The generalization of ENA equations was described by Ulanowicz [14], and the metrics used in this study, along with their significance, are summarized in Table 1. For an in-depth explanation of these equations and their foundations, please refer to [15,29,52]. The range of values defining the WoV corresponds to a degree of order that lies between 0.30 and 0.58 [23,27] or to a minimum robustness value of approximately 0.30 (considering the natural logarithm base). The result analysis focused on robustness (and, therefore, efficiency and redundancy) as an indicator of network resilience.

Table 1. Ecological network analysis flow-based metrics (3D).

Metric	Formula [1]	Name and Meaning	Reference
AMI^{3D}	$\sum_{ijk} \frac{t_{ijk}}{T_{\ldots}} \log_2\left(\frac{t_{ijk}^2 T_{\ldots}}{t_{\mathrm{ij}.} t_{i.k} t_{.jk}}\right)$	Average mutual information Order and organization of the network (efficiency)	[14,28]
H^{3D}	$-\sum_{ijk} \frac{t_{ijk}}{T_{\ldots}} \log_2\left(\frac{t_{ijk}}{T_{\ldots}}\right)$	Shannon index Diversity of flows	[14,32]
$\mathrm{H_c}^{3D}$	$\mathrm{H}^{3D} - \mathrm{AMI}^{3D}$	Residual diversity Freedom remaining in the network (redundancy)	[14,28]
R	$-\frac{\mathrm{AMI}^{3D}}{H^{3D}} \ln\left(\frac{\mathrm{AMI}^{3D}}{H^{3D}}\right)$ where $\mathrm{AMI}^{3D}/\mathrm{H}^{3D}$ is the degree of order	Robustness System's ability to persist, tradeoff between efficiency and redundancy	[24,32,37]

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

3.2. Environmental Analysis

Along with structural performance, the environmental impact of IS networks was calculated using an LCA approach. This includes the impact of material processes and the transportation between the IS entity and/or between the external environment and the IS. The indicators chosen for environmental evaluation were three midpoint impact categories based on the ReCiPe impact assessment method: climate change (GWP, quantity of CO_2 equivalent), terrestrial acidification (TAP, quantity of P equivalent) and freshwater eutrophication (FEP, quantity of N equivalent). These impact categories were selected according to the most common indicators used in LCA studies for IS. For each category, the total impact was calculated according to Equation (1):

$$\text{Impact} = \sum\nolimits_{f} q_f CF_{mf} + t_f CF_{tf} \quad (1)$$

where q_f is the quantity of flow (f), t_f is the transport of flow (f) (in quantity kilometers) and CF_f is the characterization factor (CF) for flow (f). Indices m and t refer to material and transport, respectively.

The CF was obtained from different sources (the Ecoinvent database and relevant LCA studies). During the CF selection process, attention was paid to the consistency among the impact assessment methods used to obtain the CF (here, this was the ReCiPe v1.13 method).

3.3. Case Context and Data

The methodology presented in the previous sections was applied to the Sötenas IS [50] because of the detailed documentation provided (both for network understanding and the completeness of flow data) and the network's complexity (various flows exchanged and several companies involved). Nevertheless, please note that the objective of this paper was not to provide a thorough case study of the Sötenas IS. This case was used as a basis to test different IS network structures in a realistic context (i.e., flow quantity, proportion between input/output flows and internal exchanges, and environmental considerations).

The IS presented by the authors of [50] is composed of three types of flow (material, energy and water). This study focused on the two types that were exchanged among the IS companies: material and water. To comply with the principle that in ENA calculations, a layer should be composed of flows that have an equivalent function, only the biomass flows in the materials were considered. Consequently, this study was conducted on a network composed of seven entities and two layers; thus, in the ENA calculation, $i = j = 7$ and $k = 2$. The existing IS system, as considered in this study, is presented in Figure 1.

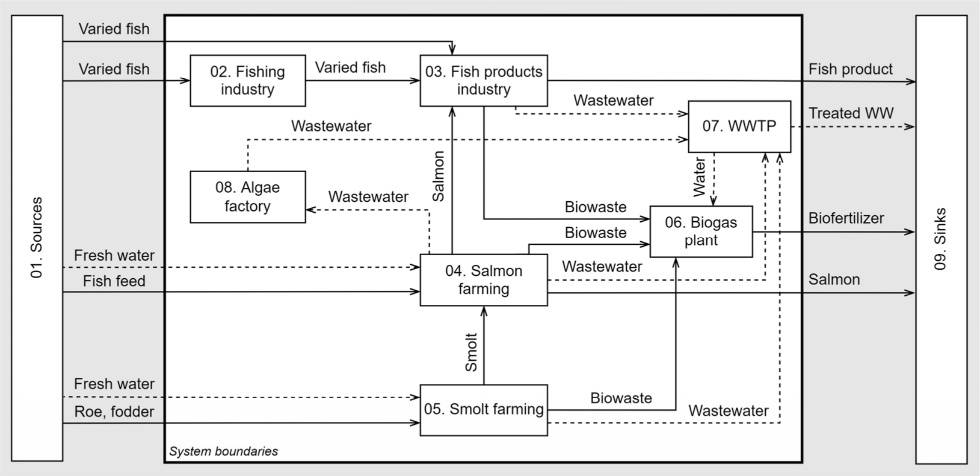

Figure 1. Flows considered in the Sötenas IS (dotted arrows = water layer; solid arrows = biomass layer; WWTP = wastewater treatment plant; WW = wastewater).

Based on the graphical representation of the network, a table was built with the information concerning both the outside and internal flows for structural and environmental analysis (starting points (i), end points (j), quantity and transportation distance). All of this information is presented in Table 2, and the entities' numeration is presented in Figure 1. All data originated from or were adapted from the data presented in [38].

Table 2. Information used to calculate structural and environmental metrics (layer #1 = material; #2 = water; the numbers in 'from' and 'to' columns refer to the numeration in Figure 1).

Flow Category	From (*i*)	To (*j*)	Layer (*k*)	Flow Type	Quantity (t)	Transport Distance (km)
Input	01	02	1	Varied fish from fishing	5.00×10^3	200
	01	03	1	Varied fish from fishing	2.79×10^4	225
	01	05	1	Roe	3.50×10^{-1}	2130
	01	05	1	Fodder (smolt feed)	2.02×10^2	100
	01	04	1	Salmon feed	7.14×10^3	100
	01	04	2	Water	5.51×10^5	0
	01	05	2	Water	5.30×10^2	0
Output	03	09	1	Fish product	1.44×10^4	200
	04	09	1	Salmon (farmed)	2.10×10^3	100
	06	09	1	Biofertilizer	3.00×10^4	100
	07	09	2	Treated WW	2.28×10^5	0
Internal	04	03	1	Salmon (farmed)	2.40×10^3	2.5
	03	06	1	Biowaste	2.79×10^4	1.5
	02	03	1	Varied fish	5.00×10^3	2.5
	05	04	1	Smolt (farmed)	1.84×10^2	0.5
	04	06	1	Biowaste	3.63×10^3	2.5
	05	06	1	Biowaste	6.09×10^1	2.5
	03	07	2	Wastewater	2.30×10^5	0
	04	07	2	Wastewater	5.49×10^4	0
	04	08	2	Wastewater	2.40×10^2	2.5
	05	07	2	Wastewater	5.30×10^2	0
	08	07	2	Wastewater	2.40×10^2	0
	07	06	2	Water	4.60×10^4	0

For each layer, choices were made regarding how to consider the system boundaries and how to apply the corresponding CF. For biomass flows, the following assumptions were made:

- Input flows carry an environmental burden from the process (with all upstream activities, as defined in the Ecoinvent database) and transport to IS;
- Internal flows carry the process used in the IS and transport between the two actors concerned with the exchange;
- Output flow burden differs according to type; in the case of a product, it carries the process used in the IS and transports it to the receiving entity; in the case of a byproduct, it carries only the transport, as the environmental impact of the byproduct is already considered in the product process.

For water flows, the following assumptions were made:

- CF for the treatment was applied to the quantity that leaves the WWTP;
- Water transport was not considered, except for the water used for its nutrient properties and exchanged in the IS (flow from 04 to 08).

Considering all of the above, the CFs applied for each type of flow and transport mode were selected, and they are displayed in Table 3.

3.4. Scenario Building

One of the goals of this study was to observe the effect of structure topology on environmental performance. To achieve this, different scenarios were built to reflect a change in the network organization, moving from a non-symbiotic situation to the existing Sötenas IS. The scenarios were classified into generations according to the complexity of the network organization (here, complexity refers to the link density). The non-symbiotic scenario was considered as generation 0, in which all flows come from and go to the external environment.

Table 3. Characterization factors considered for the studied symbiosis.

Flow Type		Characterization Factor GWP (kg CO_2eq/t)	 TAP (kg SO_2eq/t)	 FEP (kg Peq/t)	Reference
Biomass	Fodder (smolt feed)	1.49×10^3	4.45	9.60×10^{-2}	[53], adjusted with Sweden grid mix [1]
	Smolt (farmed)	4.68×10^3	4.02×10^1	1.56	
	Salmon feed	3.23×10^3	3.36×10^1	5.31	
	Salmon (farmed)	3.29×10^3	1.28×10^1	9.22×10^{-1}	
	Fish product	3.26×10^2	1.10	8.00×10^{-2}	[54] [2]
	Varied fish from fishing	2.47×10^3	5.81×10^1	9.64×10^{-3}	[55]
	Biowaste (anaerobic digestion)	1.06×10^2	1.70×10^{-1}	1.76×10^3	
Water	Water	3.30×10^{-1}	1.43×10^{-3}	2.72×10^{-5}	[55]
	Treated WW	4.72×10^{-1}	4.24×10^{-3}	9.30×10^{-4}	
	Enriched water (N and P)	1.14×10^1	5.56×10^{-2}	3.72×10^{-4}	
Transport	Truck freight	1.64×10^{-1}	3.30×10^{-4}	1.31×10^{-6}	[55]
	Aircraft freight	4.34×10^{-1}	1.71×10^{-3}	9.62×10^{-7}	

[1] Data for Sweden electricity grid mix obtained from [55]; [2] CF obtained using the ReCiPe 2016 method.

The intermediate generations were designed by referring to [4], in which various IS network topologies with three structure patterns were identified—supply chain, centered and core organization—which can be simple or with periphery. The existing network was modified by selecting the links that allowed for the construction of intermediate generations for the three structure patterns under study (the structures resulting from this process are graphically expressed in Figure 2). The number of generations associated with each structure pattern depended on the possibilities provided by the configuration of the network under study. The existing IS was considered another generation as a result of the three possible evolution pathways.

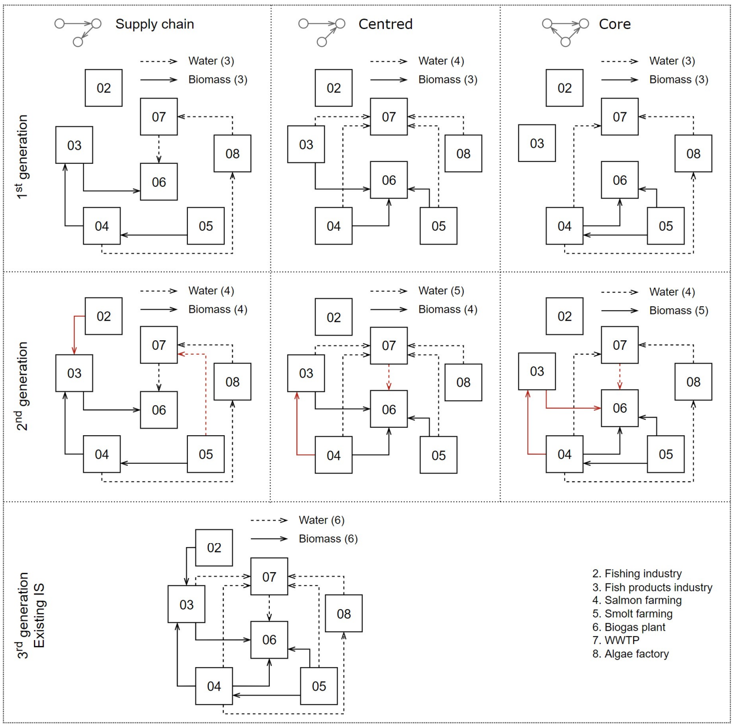

Figure 2. Structural scenarios for the three IS structure patterns (red arrows = added links; numbers in parentheses = number of links per layer).

Consequently, depending on the scenario under study, the number of input, output and internal flows varied. When an internal flow was not considered, input and output flows of an equivalent quantity were added, and CFs were applied following the same convention as that stated earlier. The main change was the transportation distance, which was greater when the flow came from outside the IS.

Based on the results obtained for the scenarios described above, a prospective approach was adopted to identify different possible configurations for a future generation of IS. Two principles guided the development of these scenarios: the creation of new flow loops to enhance interactions between the IS entities (with different intensities in redistributed flows) and shifting of processes to improve environmental performance. This is further detailed in the Results section.

4. Results

4.1. Structure Scenarios

In the case of the Sötenas IS, the scenario-building process resulted in four generations—generation 0 (non-symbiotic system); generations 1 and 2, as the progressive evolution of the three structure patterns (six scenarios—three with simple configurations and three with periphery configurations); and generation 3—with the existing network as the common evolution of the three patterns. The structures of generations 1–3 are presented in Figure 2 (for clarity, the input and output flows are not presented in the figure). Given the structure patterns, the existing IS in Sötenas can be classified as centered, as most of the flows move to the WWTP (for the water layer) or the biogas plant (for the biomass layer).

Based on the networks presented in Figure 2, the flow data needed to be adjusted according to the scenario. When an internal flow was missing, it was replaced by an equivalent flow from outside the system. The only case in which there was a change in flow type was the water exchange in the IS (between entities 04 and 08), for which an equivalent input flow of enriched water was considered, as the algae company is interested in the nutrients present in the water. For the WWTP, when flows feeding the plant were missing, the output flow quantities were adjusted with the input/output ratio of the existing IS. Moreover, when a water flow moved from a company to an external environment (without passing through the WWTP), it was assumed that water was treated (as it had to adhere to some environmental criteria to be rejected). In this case, the volume was adjusted considering the input/output ratio of the WWTP to consider the same losses in the process and apply the CF of WW treatment to the output quantity. All of the data corresponding to each assessed scenario are available in the Supplementary Materials (Tables S1–S8).

4.2. Structural and Environmental Performance

The structural performance of each scenario and the scenario ranking based on the robustness metric are displayed in Table 4. The table does not present the non-symbiotic scenario, as the results were null for each metric. The results for prospective scenarios are presented in Section 3.4.

Table 4. Structural ENA metrics for all scenarios and ranking based on the robustness metrics (GX = generation X; SC = supply chain; CT = centered; CO = core; EX = existing).

Metric Scenario	AMI^{3D}	H^{3D}	$H_c{}^{3D}$	AMI^{3D}/H^{3D}	R	Rank
G1-SC	0.59	0.59	0.00	1.00	0.000	7
G1-CT	0.47	1.18	0.71	0.39	0.367	1
G1-CO	0.36	0.45	0.09	0.81	0.172	4
G2-SC	1.00	1.20	0.20	0.83	0.154	5
G2-CT	0.99	1.63	0.64	0.61	0.302	2
G2-CO	1.39	1.67	0.28	0.83	0.152	6
G3-EX	1.07	1.72	0.65	0.62	0.296	3

Generally, the networks tended to be more efficient than redundant ($AMI^{3D} > H_c{}^{3D}$). The only exception was the G1-CT scenario, which was slightly more redundant and performed best in terms of robustness. The robustness results were discriminated according to the structure pattern; those that were centered performed better than the others, with a robustness of approximately 0.30. The third position of G3-EX confirmed that this network can be classified into the centered category. The core pattern also presented robustness values that were close (0.17 and 0.15), but the supply-chain pattern presented a greater variability in the robustness results and did not perform well ($R \leq 0.15$). There was a gap in the performances between the three best scenarios, which scored over 0.29, and the others, which scored under 0.20.

With regard to environmental performance, the results for each scenario are displayed in Table 5. In addition to the values of the three environmental impact categories, the rank of each scenario, as well as the change in ranking (based on GWP ranking), is displayed.

Table 5. Environmental indicators for all scenarios and ranking based on GWP (NS = non-symbiotic).

Metric Scenario	GWP (kg CO_2eq)	Rank and Rank Change		TAP (kg SO_2eq)	Rank and Rank Change		FEP (kg Peq)	Rank and Rank Change	
G0-NS	1.57×10^8	8	–	2.58×10^6	8	0	1.11×10^8	8	0
G1-SC	1.45×10^8	5	–	2.55×10^6	5	0	5.57×10^7	5	0
G1-CT	1.51×10^8	6	–	2.57×10^6	7	+1	5.57×10^7	7	+1
G1-CO	1.52×10^8	7	–	2.57×10^6	6	−1	5.57×10^7	6	−1
G2-SC	1.30×10^8	2	–	2.24×10^6	2	0	5.57×10^7	2	0
G2-CT	1.43×10^8	4	–	2.54×10^6	4	0	5.57×10^7	4	0
G2-CO	1.42×10^8	3	–	2.53×10^6	3	0	5.57×10^7	3	0
G3-EX	1.30×10^8	1	–	2.24×10^6	1	0	5.57×10^7	1	0

All scenarios had the same order of magnitude for the GWP and TAP indicators. For FEP, there was a deviation for G0-NS only, with a significantly higher impact than that for the other scenarios. The ranking was very similar among the three indicators. The first five scenarios were always the same and in the same order (G3-EX, G2-SC, G2-CO, G2-CT and G1-SC); the last three scenarios were the same for each indicator (G0-NS, G1-CT and G1-CO), but the order varied for TAP and FEP. Here, discrimination appeared between generations more than structure patterns. Second-generation scenarios always performed better than first-generation scenarios, regardless of the structure pattern and indicator; the environmental performance tended to increase when the network complexified. Nevertheless, the supply-chain pattern performed better than the other patterns (ranked second and fifth out of all the indicators). The existing IS ranked first among all indicators, confirming that IS systems can improve environmental performance globally.

Looking closer at the flows carrying the major environmental burden in IS, fishing had a more significant impact on the environment for the GWP and TAP indicators, and biowaste processing had a higher impact on the FEP indicator.

4.3. Multidimensional Analysis

We then focused on the relationship between the two types of performance. To analyze the environmental performance with regard to robustness, the results for each scenario, along with their environmental ranking, were plotted on the fitness curve. This is displayed in Figure 3.

Only one scenario was within the range of the WoV (G1-CT), which did not perform well at the environment level. The scenarios that were close to being in the WoV range did not perform well at the environment level, except for the G3-EX scenario, which presented a good performance overall. Most of the IS scenarios were situated on the right side of the curve, confirming the efficiency of these networks [37], in line with the results presented in Table 4. Redundant scenarios were situated on the left side, which was consistent with the G1-CT figures. Despite the position of the G0-NS marker on the left side of the curve, this scenario was not redundant; it is displayed on the curve for reference only and cannot express any robustness property, as it is a non-symbiotic scenario. The G1-SC scenario performed the worst and was strictly efficient because of the network organization; a strict supply chain with no other branches does not present alternative pathways and therefore has no redundancy [23]. Furthermore, there was a tendency toward greater efficiency from G1 to G2 for the CT and CO organizations. This was not verified for the SC pattern because of the addition of links creating an SC structure with the periphery in G2, distancing it from the strict supply chain of G1.

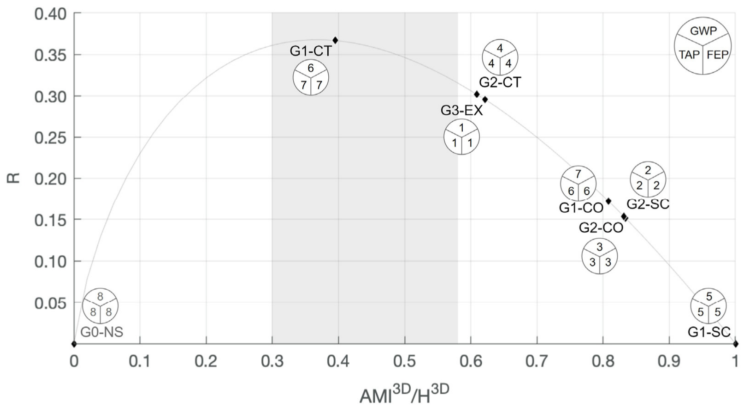

Figure 3. Scenario position on the fitness curve and environmental performance for the three indicators (gray zone = window of vitality).

4.4. *Prospective Scenarios*

Based on the results presented in the previous sections, the prospective scenarios were seen as the possible evolution of the existing network (G3-EX) and were therefore considered the fourth generation. They were built using two approaches: structure-oriented and environment-oriented approaches.

4.4.1. Structure-Oriented Approach

To exemplify this approach, a new IS structure was built considering only the water layer. The output flow from the WWTP was reinjected into entities that still had water input (04 and 05 entities), considering different percentages of the reinjected output flow. The flow entering 05 was negligible against the output flow from 07 (5.30×10^2 t vs. 2.28×10^5 t) thus, two configurations were tested for each reinjection percentage (RP) and are presented in Figure 4:

- The reinjected flow entirely entered 04; the water input was maintained, as the flow entering 04 (5.51×10^5 t) was still higher than the 07 output (Figure 4a);
- The reinjected flow was split between 04 and 05; the water input for 05 was null, as the symbiosis fulfilled the entire water demand (Figure 4b).

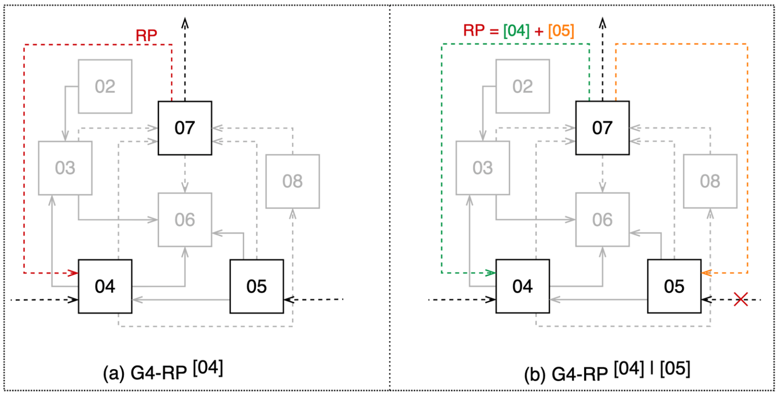

Figure 4. Structure-oriented prospective scenarios (G4 = generation #4; RP = reinjection percentage; colored arrows = added links). (**a**) One flow entering entity 04; (**b**) split flow entering entities 04 and 05.

As shown in Figure 4, one or two links were added to the network organization, reducing the volume of the input flows. Five RPs of the 07 output were considered, increasing from 20% to 100%; thus, the percentages carried by the (07-04) and (07-05) flows varied. In total, 10 scenarios in G4 were studied.

The results concerning the structural performance are displayed in Table 6. The change in tendency is expressed based on the existing scenario performance (G3-EX).

Table 6. Structural ENA metrics for the structure-oriented prospective scenarios (G4-X = reinjection percentage considered for G4; + + + = increase $\geq$ 0.25; + + = increase $\geq$ 0.15; + = increase $\leq$ 0.10).

Scenario	Metric	AMI^{3D}	Trend	H^{3D}	$H_c{}^{3D}$	Trend	AMI^{3D}/H^{3D}	R
G4-20	[04]	1.23	+ +	2.03	0.80	+ +	0.61	0.304
	[04] ∣ [05]	1.23	+ +	2.04	0.81	+ +	0.60	0.305
G4-40	[04]	1.30	+ +	2.10	0.80	+ +	0.62	0.296
	[04] ∣ [05]	1.30	+ +	2.11	0.81	+ +	0.62	0.298
G4-60	[04]	1.33	+ + +	2.10	0.77	+ +	0.63	0.289
	[04] ∣ [05]	1.33	+ + +	2.11	0.78	+ +	0.63	0.291
G4-80	[04]	1.33	+ + +	2.07	0.74	+	0.64	0.283
	[04] ∣ [05]	1.33	+ + +	2.08	0.75	+	0.64	0.285
G4-100	[04]	1.32	+ + +	2.02	0.70	+	0.65	0.278
	[04] ∣ [05]	1.32	+ + +	2.03	0.71	+	0.65	0.280

The results for all prospective scenarios tended to be more efficient (AMI^{3D} indicator) than redundant ($H_c{}^{3D}$ indicator). Although the redundancy metric tended to grow compared to G3-EX, it was slower than the efficiency metric, and $H_c{}^{3D}$ remained lower than AMI^{3D}; the maximum gap for AMI^{3D} was 0.26, whereas that for $H_c{}^{3D}$ was 0.16. An increase in RP increased AMI^{3D} (and, by force, decreased $H_c{}^{3D}$). Therefore, the robustness was not necessarily improved by the new configurations; it was only the case for 20% and 40% RP before the gap between the efficiency and redundancy metrics became too large and the network imbalance led to lower robustness. When the percentage increased beyond 40%, the robustness of the prospective scenarios was lower than that of G3-EX (R = 0.296). Nevertheless, the robustness was still better when the reinjected output flow was split to supply both the 04 and 05 entities.

When positioned on the fitness curve, as shown in Figure 5, scenarios G4-20 and G4-40 were on the right (efficient) side of the WoV (AMI^{3D}/H^{3D} > 0.58) and higher than G3-EX; the others were still on the right side but lower than G3-EX. The lower the markers were on the curve, the higher the RP was ($AMI^{3D}/H_c{}^{3D}$ ratio increased with RP); that is, the higher the RP, the more degraded the structure's performance.

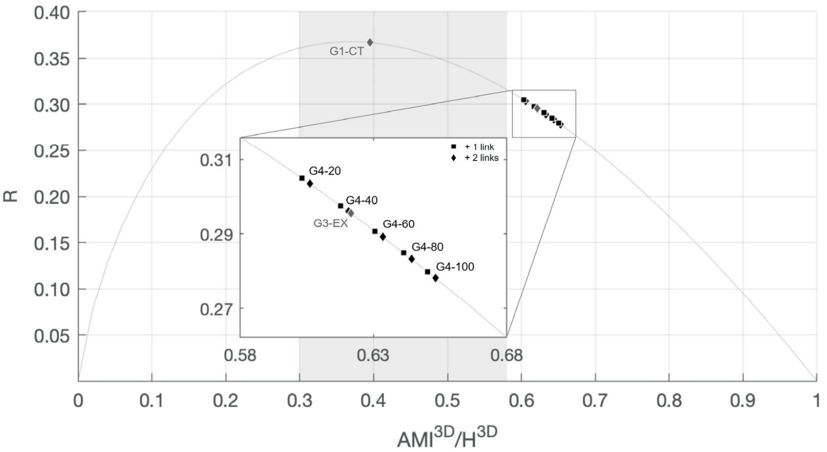

Figure 5. Structure-oriented prospective scenarios on the fitness curve.

At the environmental level, the 10 fourth-generation scenarios studied under this approach exhibited the same environmental performance; for all structure-oriented prospective scenarios, the values of environmental metrics were 1.30 × 10^8 kgCO_2eq for GWP, 2.24 × 10^6 kgSO_2eq for TAP and 5.57 × 10^7 kgPeq for FEP. They performed as well as the G3-EX scenario (they were, on average, 0.03% better for GWP, 0.01% better for TAP and less than 0.01% better for FEP) and, thus, better than the studied first- and second-generation scenarios.

4.4.2. Environment-Oriented Approach

This approach focused on the flows carrying the largest part of the environmental burden in the existing IS. Scenarios were built from the environmental performance of the existing IS based on the results presented in Section 3.2. According to the idea that IS is also a way to relocate activity and provide regional development [56], the incoming flow of fished fish was replaced by farmed salmon from the region (to target GWP and TAP indicators). For biowaste management, an alternative process was modelled by substituting biogas with composting (to target the FEP indicator). Consequently, three new scenarios were built: one with the fish shift (farmed salmon), one with the biowaste shift (composting) and one with the two changes combined (farmed salmon + composting). The CFs used for the calculation of the environmental impact of these alternative processes are displayed in the Supplementary Materials (Table S9).

Structural performance was exactly the same as that in the G3-EX scenario, as no internal flows were changed. The results for environmental indicators are displayed in Table 7 and show that no scenario improved the overall environmental performance compared to the G3-EX scenario. Nevertheless, TAP and FEP performances were globally improved (when worsened, the difference was not significant), whereas GWP was globally worsened. Scenarios with farmed salmon as the only input for the fish product industry worsened the GWP and FEP performances (not significantly for FEP) but improved the TAP performance. The composting scenario improved the GWP and FEP performances only. The scenario combining the two changes performed better for TAP and FEP indicators than the scenarios with only one change.

Table 7. Environmental metrics for environment-oriented prospective scenarios and the percentage of change compared to the G3-EX scenario (+ % = improved performance; − % = worsened performance).

Scenario	GWP (kg CO_2eq)		TAP (kg SO_2eq)		FEP (kg Peq)	
G3-EX	1.30 × 10^8		2.24 × 10^6		5.57 × 10^7	
Farmed salmon	1.57 × 10^8	−21.0%	7.54 × 10^5	+66.3%	5.57 × 10^7	−0.1%
Composting	1.28 × 10^8	+1.3%	2.29 × 10^6	−2.3%	4.42 × 10^4	+99.9%
Farmed salmon + composting	1.56 × 10^8	−19.8%	8.06 × 10^5	+64.0%	7.42 × 10^4	+99.9%

When comparing the results of these three scenarios, composting performed better for GWP and FEP. The best scenario for the TAP indicator was the farmed salmon indicator. The most significant change between the scenarios for each indicator was reflected in the two-change scenario; it worsened GWP and improved TAP because of farmed salmon, and it improved FEP because of composting.

5. Discussion

The structural evaluation of the modelized networks showed that they tend to be more efficient than redundant, which is consistent with results obtained in ENA studies applied to human systems [31,34]. This is due to the more profit-oriented organization of human-related systems compared to ecological networks. At the environmental level, results confirmed that IS configurations provide benefits compared to non-symbiotic systems for the three studied impact categories. The Sötenas IS was also found to be beneficial for GWP and TAP by the authors of [50].

When looking at the evolution in network complexity (i.e., the changes between generations), the results showed that changes in system evolution impacted environmental performance more than structural performance. From the environmental viewpoint, this confirms that the more symbiosis is advanced in terms of exchange density, the more environmental benefits are provided. Results obtained by the authors of [25] also indicate that the more a network is developed, the greater the environmental benefits. However, the environmental benefits achieved in [25] were only assessed in terms of energy savings, limiting the validation of this result. It can also be expected that network complexity can yield better structural performance and robustness, but this study did not confirm this.

Looking at the structural topology (centered, core or supply chain), the results showed that the system organization influences the structural performance more than the environmental performance. Environmental performance is not affected by the way the network entities are connected but more by 'how much' they are connected. However, at the structural level, the connection pattern influences the network robustness, which is consistent with the fact that ENA measures a network's capacity to process a medium and to have alternative ways of processing it; a supply-chain configuration performs well at the efficiency level, whereas a centered configuration performs better in terms of offering alternatives.

Thus, the results indicated that, in the studied case, an organization that favors resilience (with strengthened robustness) does not guarantee a satisfactory environmental score and vice-versa. Consequently, a tradeoff could be found with scenarios performing similarly to G2-CT (close to the WoV, with an average environmental performance). Similarly, the authors of [35] showed that the maximum resilience in energy networks incorporating renewable sources is not equivalent to the 100 % renewable sources scenario, as intuitively expected. Tradeoff conclusions were also reported by the authors of [23]; the optimal environmental network organization was not found to be optimal in terms of robustness. This reinforces the idea that solutions that seems environmentally sound are not necessarily the best choice in terms of network stability. Such conclusions highlight the usefulness of conducting both analyses to avoid overlooking a dimension, advocating for a broader decision-making process when it comes to IS design.

Structure-oriented prospective scenario results provide a new perspective on the previous results. They showed, perhaps in a counterintuitive way, that the changes in the network's organization (adding one or two links) had less influence on the robustness indicator behavior than the reinjection percentage (the markers in Figure 5 are grouped by RP and not by new network organization). This conclusion is consistent with the results reported by the authors of [35], i.e., the percentage of renewable energy influenced the robustness. Furthermore, the authors found that robustness increased with the percentage until a tipping point was reached, after which it decreased because of flows being modified in the same proportion. In the present study, we observed results because reinjecting an increasing amount of water through the same path reinforced the network efficiency. However, RP had little effect on environmental performance in the studied case. Those elements have implications for improving the IS process, as caution should be taken regarding how exchanges can occur while maintaining an acceptable structural performance.

On the environment side, prospective scenario results highlight the necessity to carefully choose the changes made to develop IS strategies on a local scale, as they can lead to counter-performances at the environmental level. When combining different changes, the tendency can be attributed to the scenario carrying the most significant environmental performance change. This opens up research perspectives on the relationship between IS in itself, with boundaries determined by the entities engaged in the network, and its surrounding environment. This raises questions about the territorial dimension of IS and its deployment as an economic development lever and environmental crisis mitigatory tool.

In addition, all prospective results highlight the relevance of hypothetical scenario simulation, as it allows us to anticipate and/or validate the IS evolution pathways. This can help decide whether new exchanges should be planned, depending on both the expected structural and environmental improvements. If it has been established that specific new exchanges allow for better robustness; these should be carried out only if (i) the environmental impact stays within an acceptable range and (ii) the new technologies required to process the output flow to use it as an input have an environmental impact that does not exceed the range between the existing impact and the expected improvement.

Despite the presented case-specific numerical results, the general findings of this study can help to guide IS planners. Even if IS design is currently focused on environmental or economic objectives, choices concerning the network organization should also be taken into consideration. The proposed approach allows for targeting of relations that contribute to strengthening the network resilience. In this way, it could complement supply-chain decision-making tools, as it helps to integrate the sustainability dimension (as suggested by the authors of [57]). It could also enrich assessment frameworks of IS sustainability and circularity (such as CELAVI [58] or the UNIDO [59]), in which the structural dimension of systems is not considered. More globally, the approach has implications for territorial planners. Indeed, the comparative analysis of IS network evolutions can help to drive territorial design in a more resilient direction, reinforcing the ability of society to adapt when facing environmental or economic variations.

Due to data availability, this study only considered some flows concerned with IS exchanges, as well as a limited number of layers. The choice of other LCA impact categories could have provided further insights regarding the qualification of the results. In future research, scenarios could be enriched with additional synergies concerning other types of flow, especially energy, which is often of concern in IS networks. Another limitation to bear in mind is the complexity of generalizing from the obtained results because of the non-linearity of the ENA results, showing complex behavior of the studied systems. On one hand, environmental performance evolves with a certain linearity, and a tendency can be anticipated (which is consistent with previous studies showing that the new exchanges developed by IS can improve the environmental impact [60]). On the other hand, structural metrics show more variability, and tendencies are therefore not easily predictable (for theoretical support of this conclusion, see [22]). To overcome the limited generalizability of ENA results, further theoretical studies applied to industrial systems can help to define the directions industrial planners should take to design resilient industrial networks. That said, ENA can be seen as a tool that reveals the behavior of complex systems by considering multiple variables (e.g., number of entities; number, position and weight of links; and multilayered networks). As emergence theory states, properties of complex systems can change with the degree of complexity, and new behaviors can appear that are different from those observed in simpler systems [56].

6. Conclusions

The intention of this research was to fill a gap in the multidimensional assessment of IS networks, with a focus on structural and environmental evaluation. This analysis was carried out with respect to the structural topology of IS networks. Based on this topology and an existing IS (Sötenas, Sweden), scenarios were built to reflect the alternatives of network deployment. Those scenarios were assessed using (i) ENA flow-based metrics (structural assessment), especially robustness, which accounts for network resilience; and (ii) an LCA approach and tools (environmental assessment) to verify the benefits provided by the synergies. Prospective scenarios were designed to further explore the structural and environmental dimensions of IS assessment. Accordingly, the aim of this research was to evaluate the link between structural and environmental performance and the behavior of metrics regarding network design alternatives.

The results showed that structural and environmental performance are not directly linked, as the best performance at the structural level does not correlate with the best results at the environmental level. Nevertheless, it was shown that topology has an impact on structural performance, and the intensity of exchanges has an impact on the environmental dimension. In the studied case, a tradeoff was found to guarantee network continuation and environmental benefits with a well-connected centered network. A prospective study provided insights into the need to carefully address IS development, as the flow volume circulating in the IS can influence structural performance. Caution should also be taken regarding technology choices depending on the IS and, more broadly, the territorial needs, as the environmental performance is sensitive to processes involved in the synergies.

Broader implications and policy directions for this study are concerned with the decision-making process for IS deployment or development. Indeed, the research conducted here advocates for a more holistic approach combining several dimensions (structural and environmental, as well as economic and social dimensions) to assure continuity in the benefits provided by IS. This reinforces the resilience of systems and, therefore, the ability of society to adapt. This study also provides insights into the ENA metrics, confirming that they are well-suited to grasping the complexity of human-related systems.

Further research is suggested to reinforce the understanding of ENA applied to IS by developing a more theoretical approach and/or operating a change in scale of assessed systems to strengthen the understanding of challenges associated with the inevitable relationships between human systems and their environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15010693/s1, Tables S1–S8: Adjusted data used for structural and environmental assessment of scenarios; Table S9: Characterization factors used for prospective scenarios.

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List of Acronyms

CF	Characterization factor
ENA	Ecological network analysis
FEP	Freshwater eutrophication potential
GWP	Global warming potential
IS	Industrial symbiosis
LCA	Life cycle analysis
RP	Reinjection percentage
TAP	Terrestrial acidification potential
WoV	Window of vitality
WWTP	Wastewater treatment plant

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