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Sustainability-based optimization criteria for industrial symbiosis: the Symbioptima case

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Abstract

The United Nations´ Sustainable Development Goals require industrial infrastructures to provide a positive impact on society by reducing waste generation and resource consumption. The enhancement and optimization of symbiotic aspects in industry clusters can support the achievement of such goals. The present paper illustrates a new quantification methodology to foster the implementation of industrial symbiosis within existing industry clusters. A Java tool has been developed to track and optimize material and energy flows within different symbiosis scenarios. The quantitative assessment is focused on identifying environmental, social and cost gains for specific Key Performance Indicators, considering a comprehensive Life Cycle Sustainability Assessment (LCSA) perspective. Furthermore, multi-criteria optimization allows to identify heuristic solutions for symbiosis scenarios. The tool has been implemented with reference to a symbiosis case from the Steel Sector. Preliminary results evidence that industrial symbiosis and industrial sustainability are complementary but different areas. Moreover, concurrent applications of such paradigms introduce a number of new challenges and operational managerial issues to be addressed.

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Keywords: LCA; LCSA; Industrial Symbiosis; Sustainable Development Goals; Optimization.

1. Introduction

The paradigm of Industrial Symbiosis (IS) implies that a group of various local entities cooperates to interchange materials, energy, water and by-products in order to obtain major benefits than the sum of individual achievable benefits from isolated entities [1].

Many of the United Nations´ Sustainable Development Goals (SDGs) [2] can be affected by the development of an industrial symbiosis, which seems to directly influence Goal n° 12 (Responsible consumption and production). According to literature evidences, IS might indirectly impact Goal n° 6 (Clean water and sanitation) [3,4,5], Goal n° 7 (Affordable and clean energy) [6], Goal n° 8 (Decent work and economic growth) [5,7] and Goal n° 13 (Climate action) [7,8,9].

The large uncertainty regarding what SDGs could be supported by IS seems due to several factors: the nature of the exchanged flows within the symbiosis, the agreed objective to build the network and contextual conditions such as environmental regulation. In the case presented by Pakarinen et al. [9] the environmental impact increased dramatically in the first stages of the enlargement of the IS, before decreasing after

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the introduction of new environmental laws and other policy measures, which triggered the introduction in the network of new technologies with the goal to reach compliance with these new standards. More in general, due to local constrains and policies it appears difficult to know a priori what and if the IS will deliver in terms of SDGs: this understanding requires the modelling of a real case study and the further optimization of key sustainability indicators.

Indeed, a key information concerns the final objective of the IS and subsequently what are the criteria and indicators for the flows optimization. As a result, complexity management of symbiotic activities has produced in literature numerous indicators as well as a lack of standardization [10]. Since IS parks are generally composed by private industries, the economic driver appears to be the main driver in the network setting. At the same time, flows circularization can lead to worsen the performances for less strategic areas, like environmental or social areas [9], in case the flow allocation bases only on economic indicators. Different authors underline the relevance of collaborative information sharing and the use of Life Cycle Assessment (LCA) methodology in order to ensure environmental congruence for single companies in a symbiosis perspective [11, 12].

The LCA application for the performance assessment of symbiosis network however faces the following specific challenges:

- *Functional unit definition*: it seems hard to identify a specific fixed product mix in a symbiotic network. In order to compare significantly two or more scenarios, these should be based on the same functional unit. Moreover, flows can be considered by-products or waste according to their actual use, and their final economic value may change from a stakeholder to another [13].
- *System boundaries:* to produce significant results, system boundaries should at least include raw material extraction and company gates to distribution for the last company using circularized flows [13]. Due to the intrinsic flexibility of networks and to different configurations, boundaries might change involving a potential non-comparability of the results.
- *Data reliability:* inventory should be based on company specific data according to a collaborative approach. The inventory of average data for all consumptions and emissions of single companies appear difficult to be rapidly collected and aligned for the assessments of a network configuration. On the other hand, the use of literature data can introduce a lack of reliability of the results.
- *Corrective assessment:* the circularization of company flows involves a technical substitution of energy and/or material flows. Such substitution suffers from different constraints like the actual demand of the material/energy and technical limits in flow substitution (i.e. quantity of a certain material that can be used for the same purpose of another material within a product without changing technical properties and quantity of the output). Furthermore, an additional intermediate processing may be required to conform a flow for a specific substitution. Another constraint could regard the technical limit in substituting a specific input with a composition of different flows (i.e. amount of different recycled materials in place of virgin material within the same product). All these constraints should be included in the model.
- *Assessment criteria:* symbiosis involves direct or indirect savings in consumption of virgin resources. In order to assess such benefits, different methodologies for credit assessments can be applied. Specifically, the assessment of avoided production is a fundamental part of the consequential LCA modelling. As a result, the use of attributional and consequential modelling depends on the purposes of the final study and from the impact magnitude of the IS on the background system [14]. More in particular, a shift of study focus towards the background system requires the use of consequential LCA [15].
- *Reference scenario:* to introduce a comparative assessment, results are often compared with a reference scenario in which flows are not circularized and companies operates as separate entities. Such scenarios, as well as alternative scenarios, are based on the assumption that multiple comparative assessments can provide the basis for a sensitivity analysis [14]. However, the symbiosis introduces potential new business models and new products with improved features: in this case, comparison with specific isolated case can be inadequate [13].
- *Integration with other decisional areas:* LCA, as well as cost-based methodologies, can be insufficient to represent the potentialities as well as barriers in creating symbiosis activities. Social and local impacts on direct stakeholders can significantly influence the final assessment at decisional level. In such sense, the introduction of Social LCA (S-LCA) and Risk indicators are emerging as relevant drivers in promoting symbiotic collaboration [16].
- *Results interpretation:* An agreed procedure for impact calculation of flexible networks can produce end-to-end impact vectors that are referred to specific configurations of symbiotic clusters. However, the optimization and interpretation of such results seems still to need further developments. Indeed, constrains quantification and assessment should avoid to include incongruent configurations.

The present paper illustrates a new quantification Java tool, named Symby-Net, to foster the implementation and optimization of industrial symbiosis within existing industry clusters, through the life cycle methodology.

2. The Symbioptima approach

The research project Symbioptima faced the problem of simulation and optimization of symbiosis activities within an industry cluster, particularly in the process industry sector [17]. The research objective is focused on providing a single company with reliable assessments in order to identify clustering opportunities for symbiotic collaboration with other companies. According to the examined literature and barriers, a series of potential developments for symbiotic assessments have been implemented within Symby-Net:

- *Sustainability key performance indicators*: the Symbioptima approach is based on a Life Cycle Thinking, which means that, each symbiotic activity contributes to an overall impact of the network through a cradle-to-gate additional impact. Normalization and weighting are not considered, as weighting is not generally recommended in comparative studies due to its subjectivity [18]. Conversely, midpoint indicators of economic, environmental and social impact assessment are combined to provide an overall Life Cycle Sustainability Assessment (LCSA) profile. Moreover, risk indicators concerning potential worker's health are assessed.
- *Optimization approach*: Symby-Net aims to identify the best symbiosis scenario within a number of potential options with different potential partners and flows in order to minimize selected LCSA midpoint impact categories. Quantities of each flow can also vary in presence of a fixed network, where members of the cluster do not change. In this case, Symby-Net aims to identify the optimal flow distribution among such companies.
- *Bottom-up approach*: producers and buyers of waste flows and by-products constitute a flexible symbiotic network. Each node represents a single company or a single production facility. The network has not any specific purpose and is based on a flexible aggregation of different elements. This means that collaboration can be exploited at local level within a fixed number of partners or by network expansion through the introduction of new members.
- *Open symbiosis configuration*: it implies that each company can adopt symbiotic activities based on specific benefits with different partners, not limited in a local area. The approach allows monitoring both direct and remote symbiosis activities (e.g. purchasing of products containing recycled materials).
- *Smart inventory*: Symby-Net is designed in order to reduce the complexity of symbiosis modelling by identifying only flows that can be circularized on a physical basis and avoiding tracking for each company the whole inventory of energy and mass flows. Furthermore, information is integrated as Independent Information Modules (IIMs) in order to have local control of quality assessment and to improve usability as in [19]. In case the network is arranged in presence of data scarcity from some players, average data from commercial database can be used. In this way, the user is required to provide a minimal set of data that are quantities, properties, origins and destinations of both circularized flows and flows that can be partially or totally replaced. Hence, geographical characterization of the impact of the IS players can be enclosed in the LCSA profile.

The following paragraphs describe the logical sequence of computational activities as progressive phases.

2.1. Identification and substitution of symbiotic flows

Symby-Net focuses on those input or output flows of production units that can potentially be reused or substituted within the IS, these energy and material flows are called "symbiotic flows". The sustainability assessment is related to different production units (Z in Figure 1) within a network consuming resources and producing goods and emissions. Impacts related to end-of-life treatments are allocated to the producer of the waste flow. Flows that are interchanged among different companies, either mass or energy, are associated to arrows connecting one player to another.

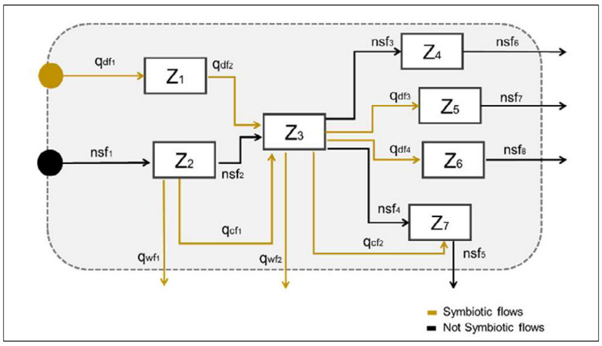


Figure 1 – Identification of symbiotic flows within an industry cluster

A scenario can describe a specific flow distribution among the same members, the introduction of new members or a combination of these two cases. In order to maintain a congruent description and comparison among scenarios, the following hypothesis have been implemented:

- The description of material and energy circularization is performed by adopting an attributional perspective in which flow quantities and destinations can vary between a player to another on a flexible basis, with the only constraints due to physical, technical and demand/offer balance limits. IS networks can be considered as multifunctional systems, that produce several main products and by-products, that changes output according to a specific configuration and market demand [14]. The IS output of main products in a specific time span is the functional unit and should therefore be constant in all compared scenarios.
- To each substituting flow are associated two parameters: a Substitution Ratio (SR), which can take into account different technical properties between the substituting and the substituted flow, and the maximum percentage that can be substituted without altering the quality of the PU product.
- Intermediate processes that may be needed to adapt, for example, a waste flow to a certain reuse, are accounted in terms of additional impact.

2.2. LCSA modularization

In order to introduce a certain degree of flexibility in the modelling overall effects of single incremental activities are modelled through Independent Information Modules (IIMs). This approach has been applied to product chain areas to calculate the environmental impact of complex supply chains [20].

Modularization is firstly applied to describe company activities, which are grouped with reference to specific

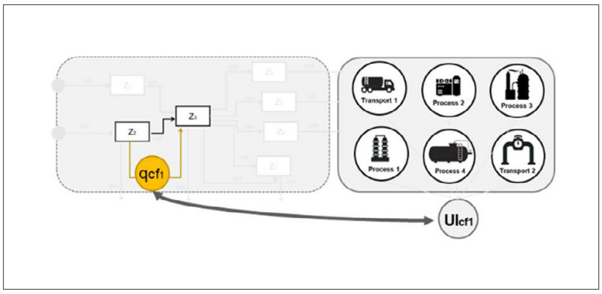


Figure 2 – Association of unitary impact to circularized symbiotic flow and related treatment processes

symbiotic flows (e.g. set of sub-processes for transforming organic by-product for a specific use within the cluster).

Modularization is then applied to calculate the related impacts; an LCSA profile is calculated through the linear combination of flow quantities and their respective LCSA Unitary Impacts (UI). A UI is a vector representing a set of midpoint effects for the grouped processes referred to a specific symbiotic flow (e.g. UI includes characterization vector in the LCA perspective). Symbiotic flows can be separated in circularized flows (*cf*), direct flows (*df*) and waste flows (*wf*). The first are referred to by-products that are reused within IS, the second are flows from the technosphere that are related to virgin resources consumption and transformation, while waste flows are destined to controlled dismissal without any further reuse in the IS.

The sustainability impact I_{LCSA} for each symbiotic flow is calculated by a multiplication of Unitary Impacts (UI) and respective quantities (q_i, q_j and q_k); z_1 and z_2 represent respectively the origin and destination Production Unit (PU) for a flow. Considering a given (z_1, z_2), the impact of circularized flows is assessed in (1) by adding the impacts of the transportation process (*tr*) from one PU to another and the impacts of intermediate processes (*ip*) to adapt the flow to a specific use (e.g. purification of a hazardous material) in the time span T. The impact of direct flows is assessed in (2) by adding the background (*bg*) impacts of transformation processes along the product chain from extraction phase up to PU gate. Finally, in (3) impacts of waste flows are assessed by considering transportation to dismissal and end-of-life (*eol*) operations.

$$\boldsymbol{I_{LCSA}}(cf_{i,z1,z2}) = \left(\sum_{t=1}^{T}([\mathbf{UI}_i]_{\ tr} + [\mathbf{UI}_i]_{\ ip})\right) * q_{i,z1,z2} \quad (1)$$

$$\boldsymbol{I_{LCSA}}(df_{j,z1,z2}) = \left(\sum_{t=1}^{T}[\mathbf{UI}_j]_{bg}\right) * q_{j,z1,z2} \quad (2)$$

$$\boldsymbol{I_{LCSA}}(wf_{k,z1,z2}) = \left(\sum_{t=1}^{T}[\mathbf{UI}_k]_{tr} + [\mathbf{UI}_k]_{eol}\right) * q_{k,z1\_z2} \quad (3)$$

UI can be calculated through both average data and company-specific data. The first option can be applied in a data scarcity context: in this case, the UI reports the sustainability profile for the average processing technology, while the latter should be preferred in the case of a highly collaborative symbiotic cluster.

2.3. Identification of key performance indicators

In order to assess the effect of symbiotic activities key parameters have been identified. In particular, traditional economic indicators that are related to flow purchasing and selling (i.e. cost for purchasing a certain material that are calculated with the Life Cycle Costing methodology) are complemented with other environmental, social and risk indicators. Environmental indicators are referred to LCA midpoint impact assessment categories (e.g. Global Warming Potential), while social impacts are referred to Social Life Cycle Assessment (S-LCA) indicators. Prospectively, such parameters are thought to be supplemented with social data related to local stakeholders.

Finally, risk indicators are referred to potential negative effect in the direct use of a specific material or energy. A risk category is associated to each symbiotic flow according to potential health problems for single operator employed in the IS network [21].

2.4. Assessment of Symbiotic potential

Once the sustainability impacts have been modularized, it becomes possible to simulate the LCSA impact of different configuration of the IS in the single company or in the multiple company perspective. In the equation system (4) impacts for the selected midpoint impact categories are assessed for a given Production Unit ($\bar{z}$) in a specific scenario (A).

$$\boldsymbol{I_{\bar{z}}}(A) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{z1=1,z1\neq\bar{z}}^{Z}\Big(\boldsymbol{I_{LCSA}}(cf_{i,z1,\bar{z}}) + \boldsymbol{I_{LCSA}}(df_{j,z1,\bar{z}}) + \boldsymbol{I_{LCSA}}(wf_{k,z1,\bar{z}})\Big) \quad (4)$$

The first equation of the system (5) represents the difference between impacts of two scenarios (A, B) taking into consideration all the linked production units (Z) in all combinations without double counting. This first equation is also assessed by Symby-Net with the reference of a given production unit ($\bar{z}$), to highlight the performance variation of a single company of the IS. The second equation in (5) represents the structure of the physical, technical and economic constraints, while the third equation represent the limit on physical flow variation: the mass balance in flows substitution should take into account technical properties of the concerned flows, hence it is introduced a Substitution Ratio (SR).

$$\begin{cases} \boldsymbol{I_Z}(\mathrm{A,B}) = \sum_{z=1}^{Z}\big(\boldsymbol{I_z}(B) - \boldsymbol{I_z}(A)\big) \quad (5) \\ \boldsymbol{\rho} \leq \bar{\boldsymbol{\rho}} \\ \big(q_{i,z1,\bar{z}}(B) - q_{i,z1,\bar{z}}(A)\big) * SR_{i,j} = \\ \quad = \big(q_{j,z1,\bar{z}}(B) - d_{j,z1,\bar{z}}(A)\big), z_1 \neq \bar{z}, \forall z_1, \bar{z} \in \mathrm{Z} \end{cases}$$

The incremental impacts are considered respect to a reference condition (e.g. scenario where production units are not performing any symbiosis activity or the present IS configuration).

2.5. Optimization algorithm

Simulation models can be linked with optimization criteria by the implementation of methods like mathematical programming (i.e. single objective and multi-objective criteria) and heuristic methods (i.e. simple heuristic, meta-heuristic, artificial intelligence) [22]. In the multi-objective problem, the objective is the impact minimization for a given LCSA impact category within the production units within the IS. The user has the possibility to select which LCSA impact categories should be optimized. Symby-Net produces optimal values for these impact categories, while the non-optimized LCSA impact categories and risk indicators are assessed ex-post.

The IS optimization phase should take place after each PU of the IS has optimized its own processes in order to reach the desired output of the PU main product. This first optimization should be performed before data are fed into Symby-Net.

Since LCSA impact categories may have different units of measurement, one objective function is optimized, while the others are used as constraints following the epsilon-constraint method [23]. To solve the problem, a heuristic approach is developed according to two goals: the efficient identification of the epsilon thresholds used in the epsilon-constraints method and the smart modification of these epsilons in order to quickly obtain optimal solutions. The output of the optimization is the identification of a set of optimal symbiotic scenarios: e.g. optimal allocation of flows among IS companies.

The objective function $f_n(q)$ of the problem is represented in equation (6).

$$min\ f_n(q) = min \sum_{z1=1}^{Z} \sum_{z2=1}^{Z} \sum_{w=1}^{W} UI_w * q_{w,z1,z2}\ ,$$
$$n \in N^*, z_1 \neq z_2; z_1, z_2 \in Z; w \in W = (I \cup J \cup K) \qquad (6)$$

Such objective function represents the minimization of exchanged flows (q), each weighted on the Unitary Impact (*UI*) of the chosen impact category, while the other objectives follow as constraints. In (6), n is an impact category among the N^* that are chosen to be optimized, z_1 and z_2 are different production unit of the IS, while w is a symbiotic flow among all the possible symbiotic flows W. In this way, by considering as an example an environmental impact category, equation minimizes the interchanged flows with the maximum impacts.

The resulting problem can be treated as a weighted max-flow one, namely a linear programming problem that can be solved using with specific algorithms to fasten the construction of the solution [24]. In general, the dimension of the problem can be as complex as the number of the interchangeable flows. Finally, it is worth nothing that the network underlying the formulation proposed is not complete, but the generated arrows represent only the feasible symbiotic flows.

3. Results and discussion

Symby-Net was preliminarily tested to model configurations in the exemplificative case of a network of nine players (foundry, cement factory, brick factory and paper mill, three dismissal facilities and two companies producing traditional products).

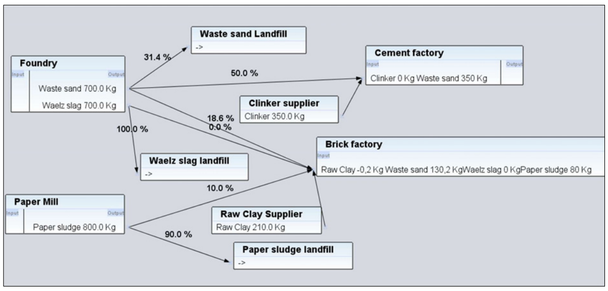


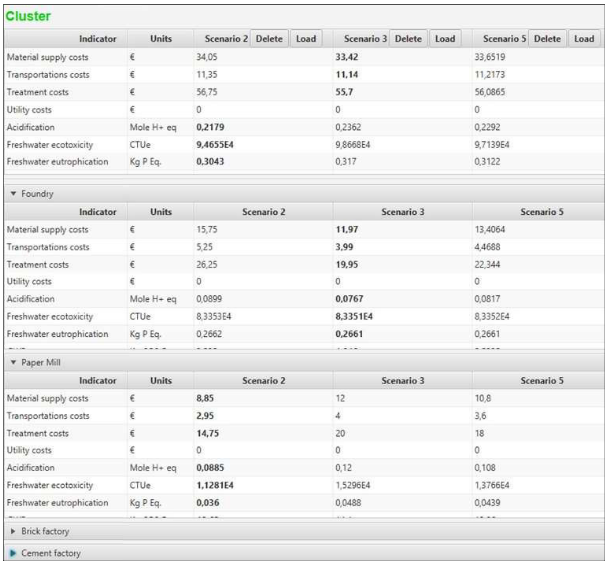
Figure 3 – Modelling of IS network in Symby-Net

Waelz slag and waste sand can substitute clay in the brick factory; waste sand can also substitute clinker in the cement production, finally paper sludge can substitute clay in the brick production. The different technical properties of these potential symbiotic flows are translated into constraints such as different substitution ratios and maximum percentages of substitution. Hence, the network and the related flows substitutions are modelled (Figure 3) and the LCSA impact categories to be optimized are selected, the optimization is run and automatically produces a set of scenarios.

For explanatory purpose, only two impact categories are optimized: an LCC indicator and a climate change indicator. In a first step, two scenarios are produced considering one objective function at a time: in this way the optimal threshold for both categories is found. This means that in a multi-objective optimization the values obtained for these two impact categories cannot be lower than the respective thresholds. The second step is the application of the epsilon-constraints method: in this example the only constraint is the second objective function, the starting epsilon is equal to the respective threshold. Since the thresholds are part of two different scenarios, the problem generated an empty admissible region. Therefore, the epsilon is gradually increased until the minimized objective function reaches its threshold value. This allows to identify the border of the admissible region, made of optimal scenarios.

Symby-Net provides an assessment of the sustainability profile for the use of symbiotic flows at two different levels. At IS level, a sustainability profile can be assessed as overall contribution of the processes linked to symbiotic flows for each scenario. At factory level, Symby-Net assesses key performance indicators of the single production unit (i.e. Foundry in Figure 4). Then, the best key performance values are highlighted in bold within the final table (Figure 4). Since in the third scenario both indicators are optimized, the resulting performance values are more equilibrated as a whole but singularly worse than those obtained in the other scenarios. Moreover, Symby-Net allows the calculation of the symbiotic potential in graphical terms as percentage variation of each indicator with reference to a chosen benchmark scenario (every calculated scenario can be selected as benchmark).

Symby-Net identifies the best scenarios for implementation, hence seems suitable for the use by a company manager exploring possible cooperation projects and/or by an industrial park manager implementing sustainability policy. This bottom-up perspective in the assessment set-up can encourage the involvement of new different players in the IS network



Cluster

Indicator	Units	Scenario 2	Scenario 3	Scenario 5
Material supply costs	€	34,05	33,42	33,6519
Transportations costs	€	11,35	11,14	11,2173
Treatment costs	€	56,75	55,7	56,0865
Utility costs	€	0	0	0
Acidification	Mole H+ eq	0,2179	0,2362	0,2292
Freshwater ecotoxicity	CTUe	9,4655E4	9,8668E4	9,7139E4
Freshwater eutrophication	Kg P Eq.	0,3043	0,317	0,3122

Foundry

Indicator	Units	Scenario 2	Scenario 3	Scenario 5
Material supply costs	€	15,75	11,97	13,4064
Transportations costs	€	5,25	3,99	4,4688
Treatment costs	€	26,25	19,95	22,344
Utility costs	€	0	0	0
Acidification	Mole H+ eq	0,0899	0,0767	0,0817
Freshwater ecotoxicity	CTUe	8,3353E4	8,3351E4	8,3352E4
Freshwater eutrophication	Kg P Eq.	0,2662	0,2661	0,2661

Paper Mill

Indicator	Units	Scenario 2	Scenario 3	Scenario 5
Material supply costs	€	8,85	12	10,8
Transportations costs	€	2,95	4	3,6
Treatment costs	€	14,75	20	18
Utility costs	€	0	0	0
Acidification	Mole H+ eq	0,0885	0,12	0,108
Freshwater ecotoxicity	CTUe	1,1281E4	1,5296E4	1,3766E4
Freshwater eutrophication	Kg P Eq.	0,036	0,0488	0,0439

Brick factory

Cement factory

Figure 4 –Sustainability profile for three optimized scenarios

according to an open symbiosis point of view. It is possible, though, that the inclusion a new player may bring benefits at IS level but not for the new single player: in this case, Symby-Net can provide basis for new business models involving compensation to specific players.

4. Conclusions

The presented Symby-Net is able to provide a Life Cycle Sustainability Assessment of symbiotic networks. Moreover, Symby-Net offers the option to identify optimal flows configurations by minimizing a set of selected indicators. As discussed above, the concept of IS alone seems not to assure benefits in any SDG but the Goal on Responsible consumption and production. Furthermore, the relation among LCSA impact categories and SDGs is not always direct and without overlapping.

The use of the presented tool, namely in the model realization and in the selection of the optimized impact categories, may contribute to reduce uncertainty in policy application and related effects within Industrial Symbiosis networks.

Open issue relates both to applicative integration and methodological barriers. The application of Symby-Net to complex IS networks could fully explore the optimization features by emphasizing differences with other IS management tools. In methodological terms, perspective issues regard the alignment of assumptions with IS operational routines (e.g. time span for proper comparison, effect of stock quantities within single companies etc.) and the inclusion of impacts for infrastructure building within the assessment (e.g. the building of an additional pipeline for flow distribution). Related to the latter problem, in the present version of Symby-Net it is not possible to implement the amortization rate of infrastructure since it would likely imply a longer time span compared to the one considered in the modelling.

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