Modelling of an industrial symbiosis network as a supply chain

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Abstract

Industrial symbiosis pursues the implementation of synergies among companies in terms of ensuring a beneficial coexistence, not only environmental but also economic and social. This involves cross-industry and cross-sectorial collaboration within a community approach, providing a competitive advantage through exchanges of material, energy and water. Collaboration and synergistic possibilities offered by geographic proximity underlie successfully implemented experiences. This work aims at conceiving the entities involved as suppliers, receivers and processes in analogy with a supply chain. An industrial symbiosis supply chain model has been developed so that firms can understand the industrial symbiosis opportunities that they might have in comparison to a traditional supply chain of resources. The model was implemented computationally with a supply chain-based software tool in order to analyse and experiment with a primary industrial symbiosis network of three large companies from the process industry. The performance of the network model has been outlined with a focus on resilience under several fluctuations that might happen with regard to the resources exchanged. In brief, this methodology provides a complementary approach to the feasibility studies of industrial symbiosis projects at the design stages so as to support the decision-making about implementing new resource efficiency-based configurations that should perform as sustainable supply chains.

Keywords
Industrial symbiosis network, supply chain performance, modelling and analysis

1. Introduction

The concept of Industrial Symbiosis (IS) belongs to the recent field of sustainability of Industrial Ecology. As described by Graedel & Allenby [1], *Industrial Ecology consists of a systemic vision which seeks to optimize the whole material cycle from their virgin extraction, through the finished material, the component, the final product, the product obsolescence and its final disposal*. On the basis of this statement, IS incorporates many elements that emphasize the idea of completing cycles within an industrial process and the reuse of materials from a broad systemic perspective.

IS involves traditionally separated sectors performing different activities within a community approach, providing a competitive advantage through a physical exchange of residual materials, energy and water. Realization of IS mainly relies on the collaboration and synergistic possibilities offered by geographic proximity of the entities involved [2]. This has been widely exampled in the case of the small town of Kalundborg in Denmark, where a dense network of interactions between the entities that formed the town's industrial park had emerged spontaneously [3]. There are also recent cases like Ulsan [4] in which these networks were developed intentionally by planning so as to achieve a more sustainable industrial activity while improving economic development.

Whatever the mechanisms needed to start, speed and scale up IS, the individual process and manufacturing activities have to face a wider approach of the operations that occur within the plant in order to ensure new business opportunities for increasing non-labour resource efficiency while strengthening and valuing the labour force. More diverse and wider cross-industry and cross-sectorial networks will emerge along with new partners and patterns of the supply chain.

This work aims at understanding this configuration in order to make it simpler and more familiar for the entities involved in potential synergy networks of industrial regions, parks or clusters. A supporting method is developed to visualize and analyse the performance of an IS network as a supply chain. Industrial symbiosis synergies and supply chain principles are explored and both approaches are merged into the Industrial Symbiosis Supply Chain conceptual model (ISSC). The ISSC model was implemented computationally and applied to an industrial complex in Northern Spain where earlier synergies had been detected [5, 6]. As a result, an innovative methodology is provided within this work and it shows how this could help the decision-making process for the design of an industrial symbiosis network.

2. Industrial symbiosis network and supply chain analogy

2.1. Industrial symbiosis synergies

An industrial symbiosis network relies on the concept of synergy. According to the Oxford Dictionary, synergy means *the interaction or cooperation of two or more* *organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects*. With the focus on profits and economic potential for the implementation of synergies and beyond quantifying the savings of natural resource consumption and waste generated within the industrial system, a life cycle approach is also essential to assess the environmental and social benefits in terms of sustainability of the IS network model [7]. The positive impact is in principle favoured by geographical proximity between the members participating in the synergy.

The collaboration opportunities or synergies can be classified into three major groups [8]. *Substitution synergies* refer to flow exchanges, for which the consumption of a company's inflow is replaced by a residual output from another company. Additional cooperation is based on *mutualisation synergies* for the integration and sharing of assets such as infrastructure and services required for the companies within the system to reduce the demand for resources. And a third type named *genesis synergies* implements both substitution and mutualisation synergies, consisting of the creation of new activities or relocation of the existing ones given the existence of profitable business opportunities [9].

2.2. Industrial Symbiosis Supply Chain model (ISSC)

The analogy between a supply chain and an IS network underlies the insights obtained in a previous work, in which a methodology was developed to provide guidelines in undertaking IS projects in an industrialized area of Northern Spain [6]. The industrial system was made of large companies from the process industry situated in an industrial complex and SME's in industrial parks. The performance of the supply chain and the potential synergies specifically identified for the process industry companies unveiled an analogy between the two concepts, contributing to this new approach of analysis.

Blanchard [10] defines supply chain as *the sequence of events that cover the entire lifecycle of a product or service from conception until it is consumed*. Within this broad definition, there are a wide variety of models of supply chain. The Supply Chain Operations References (SCOR), has become a reference for the management of the supply chain [11]. This model ranges from the supplier's supplier to the customer's customer. In this paper, the supply chain model is simplified to a subset of the initial SCOR model, shown in figure 1. The simplification includes from the supplier to delivery to the customer or destination, omitting any event beyond its limits thereby adjusting the boundaries of the system under study.

Looking at the IS network in analogy with a supply chain of suppliers and clients, an industrial synergy-based conceptual Industrial Symbiosis Supply Chain (ISSC) model comes up, as is depicted in figure 2. The model represents the wide variety of synergies that can occur in a network given the three types considered before. The model structure may include any possible case so that all of them are represented by a single idea that suits each case as necessary.

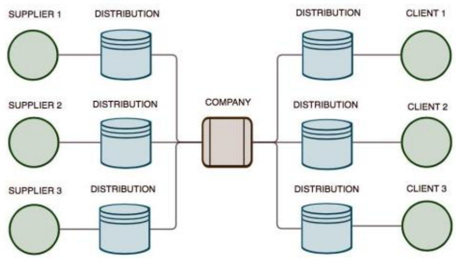

Figure 1. Supply Chain Operations References model [11].

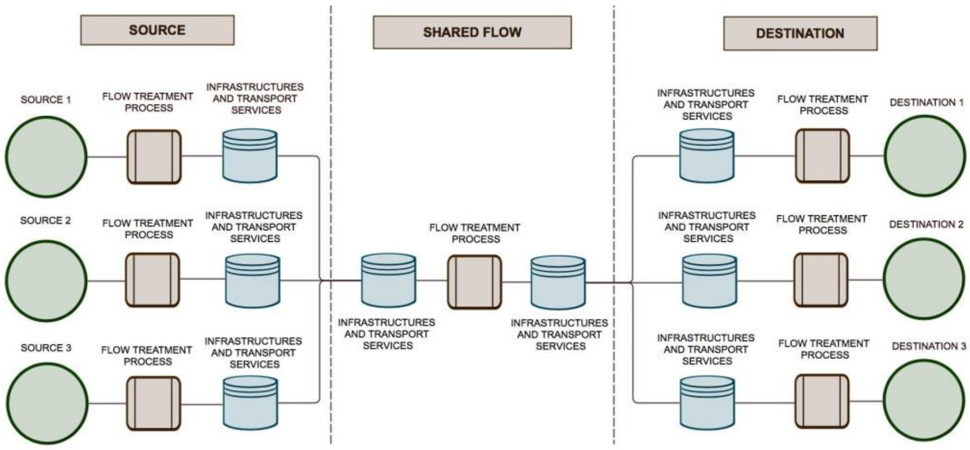

Figure 2. Industrial Symbiosis Supply Chain model (ISSC).

The elements or entities in both models pictured in figure 1 and figure 2 maintain a conceptual analogy. The *Source* entity in the ISSC model has a direct relationship with the supply chain provider or supplier concept. In both cases these entities provide flows of resources or products that will be further processed or directly distributed to their respective destinations. The *Destination* entity considered in the ISSC model corresponds to the client or receiver of the finished products in the supply chain SCOR model. These entities act as sinks of the final product and endings of flows. The production process in a supply chain maintains a direct analogy with the processes used for the adaptation of a flow in an industrial synergy; the *Flow treatment process* in the ISSC model. They can be a series of successive processes to achieve the desired product specifications. Finally the distribution, not only of the finished product to the customer, but also of any flow movement along the supply chain, have their equivalence in concept with *Infrastructures of transport and services* that are represented in the ISSC synergy model. The flexibility of the model enables the omission of the elements that might not be necessary when working with the design of the synergy network.

3. Methodology for synergy analysis and initial network proposal

This work begins by designing a primary network based on 19 potential synergies identified among three large companies from the process industry that had participated in a previous project [6]. From this range, a preliminary selection of those technically, economically and environmentally feasible has been selected. An initial synergy network came up to be designed and analysed according to the ISSC model. The main steps followed are briefly described below.

3.1. Preliminary technical selection of synergies

A preliminary selection of the synergies forming the symbiosis network was performed. The criteria identified for this analysis were supply capacity, availability of technology, flow purity, infrastructure, facilities and services needed, forecasting of technological and industrial investment and specific weight of exchanged flow over the total production [17]. The selection used a multi-criteria linear scoring method to rank and prioritise the synergies. The weighting of the criteria was equal for all cases, using a priority selection scale that varied from 0.25 in the case that less met each criterion and 1 for the case that best met the specifications. Synergies with the highest score were those considered as smarter and affordable in terms of low-tech requirements and faster in order to facilitate the creation of a primary synergy network open to future growth. Within these ranked synergies that overcome the prioritising targets, a further economic and environmental feasibility assessment was done.

3.2. Economic feasibility of the technical viable synergies

The assessment of the economic feasibility of implementing each synergy individually and as a whole network was supported on estimation methods. An order of magnitude of the capital, operating and maintenance costs were valued for each case along with the savings obtained for the new synergy management.

In order to estimate the costs associated with the implementation of a synergy, two distinct parts to its calculation were proposed: a part of processing or treatment of the synergy flow and another part of transportation of the flow between each of the entities involved. In the first part, the Module Costing Technique developed by Turton et al. [12] was used. The equipment module costing technique is a common technique to estimate the cost of a new plant. It is generally accepted as the best for making preliminary cost estimates. From this method, both the capital costs and the costs of operation and maintenance of the new facilities were obtained. In the second part, the transport cost estimation was considered for both types of flow, fluid and solid. For the transport of fluids in pipes, the calculation was simplified for piping and pumping stations [13,14]. In the solid transport case, the cost was estimated for road transport, basing this calculation on the prices offered by the software Acotram® from year 2008, which is a Transportation Costing Software offered by the Ministry of Public Works and Transport of the Government of Spain. In the case of occurrence of activities that are not considered in the module costing technique, specific methods should be considered such as the one based on the Barnstable County Wastewater Cost Task Force estimation costs for wastewater treatment plants [15]. As a result of this economic analysis, those synergies which did not fulfil the profitability requirements were discarded from the methodology. The ones which proved to be economically viable continued being analysed in order to estimate their environmental impact.

3.3. Environmental feasibility of the technical-economic viable synergies

This step aims at analysing and comparing the environmental impact of the selected synergies that were also tested as economically viable. For this purpose a life cycle analysis of the operation with the synergy implementation case was carried out and compared with a life cycle analysis of the base scenario in which the synergy was not implemented. The carbon footprint was used as the indicator to compare both scenarios [16]. Based on this indicator, any synergy would be environmentally feasible when the carbon footprint of the new flow management after the synergy implantation is reasonably lower than the one left by the previous management.

3.4. Proposal of the initial synergy network

Finally, those synergies that best suited the sustainability principles formed the preliminary IS synergy network to be implemented firstly. Results of the analysis turned out 3 main selected synergies to take part in the initial synergy network [17]. Table 1 represents the 3 selected synergies that took part in the analysis of the network. These synergies formed the new industrial symbiosis synergies network as is represented in figure 3.

Table 1. Synergies selected after the feasibility analysis.

Code	Synergy	Type	Companies involved
MM1	Common supplier of auxiliary material	Mutualisation	C1, C2, C3
MM3	Shared management of hazardous waste	Mutualisation	C1, C2, C3
MM4	Shared management of non-hazardous waste	Mutualisation	C1, C2

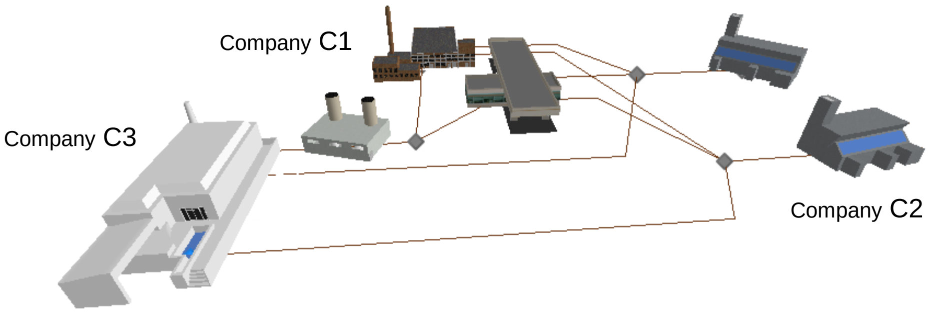

Figure 3. Proposal of the initial synergy network.

4. Computational modelling and analysis

The ISSC analogy directly related the entities of the industrial synergy model with a supply chain. The analysis and behaviour of an IS network at supply chain events can be a very complex process that requires computational modelling. Additionally, it is necessary an equivalence of the input variables and the variables used to quantify the performance of both IS processes and supply chain models. Input variables such as production or transport distance and output variables such as operating costs were used to define both approaches in this analogy.

The computational modelling was performed in the intelligent object programming environment Simio®. Each of the entities involved in the ISSC synergy model had their direct equivalence according to the entities of a supply chain for which Simio® used the corresponding generic intelligent objects. These objects were defined to adapt to the characteristics of the network to be simulated. Variability and performance of the network model was quantified through the computational analysis in order to analyse its resilience to perturbation.

4.1 Performance assessment of the ISSC model

A wide number of categories of variables exist to assess a supply chain performance. Neely et al. [18] present some of these categories as quality, time, flexibility, and cost. Although two measures of performance used in the vast majority of supply chain models predominate [19]. These are costs and customer service. Costs correspond both to the capital costs and inventory investment and the operating costs of the company. In turn, the customer service variables include time for goods transport, possible failures in service due to lack of stock, and the customer supply capacity. In this work, two of the analysis variables exposed by Beamon [19] are considered: operating costs and the reduction of customer supply capacity.

4.2. Resilience measure of the ISSC model

The concept of resilience in the supply chain literature addresses the operational and financial performance in the interconnected, dynamic business environment that is subject to fast and significant changes [20]. For example, Christopher and Peck [21] defined resilience as the *ability of a system to return to its original state or move to a new, more desirable state after being disturbed*. Walker et al. [22] construct a different understanding of resilience applicable more directly to natural systems. They describe the critical aspects of resilience as latitude, resistance, precariousness and anarchy. From sustainable industrial system approaches, resilience measures and main features may vary from complex adaptive system views [23] and engineered network theories [24]. Given the ISSC model provided in this work, the framework of Walker et al. [22] has been chosen to best recognize the resilience of the case study. *Latitude* refers to the elastic range in which a system can be perturbed or deformed without losing the ability to return to its original form. *Resistance* is the difficulty or force required to create a unit change in the system. *Precariousness* describes how close the system is to exceeding the elastic threshold and undergoing a permanent restructuring. Lastly, *anarchy* refers to cross-scale interactions and how perturbations at one scale may create regime shifts. In this work, only the latitude and the resistance of the system were considered to analyse the resilience of the synergy network. In this case latitude referred to the maximum range between the initial case operating costs and the ones in the scenario for the amount reduction of supplied products. The larger the range between the two operating cost situations, the greater the resilience of the network for this type of perturbation. Resistance is the chance to make a unit change in the system. In this synergy network replication was represented by the slope of the operating costs of the system during the disturbance due to supply shortage. The greater the slope in the graph, the lower the network resilience to such disruption.

5. Results and Discussion

The results were given for one of the scenarios investigated that consisted of reducing the volume of production and therefore the amount of resources and waste products supplied in each synergy. Operating costs were used as the output variable in the calculations to study the response of the system to the drop. Therefore, the input variable in the analysis was the reduction of exchanged or shared products for each synergy. Each scenario was considered for each of the synergies individually. The results for each company and the network as a unit were compared in order to find the resilience of the system.

This situation influenced the allocation of costs and profitability at the network. Considering the response of the network to the situation and the evolution of its operating costs, the resilience of the network to the disturbance scenario was concluded. The results of the analysis for synergies MM1, MM3 and MM4 are shown in figures 4, 5 and 6 respectively.

The nomenclature of the figures includes each of the cases studied during the analysis of the initial system and the IS network. R represents the initial case of the system without the implementation of the synergy network. IS_i represents the industrial symbiosis network i being each of the simulated scenarios, $IS_{1.2}$ for this scenario case and IS_0 the base case in absence of variability. $C_{j,i}$ represents the companies of the system j being the indicator of each company that is involved in each synergy.

The comparison of the $IS_{1.2}$ with R shapes for MM1 synergy in figure 4 shows that as production declines the savings produced by this implantation are reduced without getting to be zero. Therefore the latitude of the network will be lower as the reduction of the product supply increases. The resistance stays low and constant throughout the experiment, keeping the cost slope the same for all the scenario rates. It can be observed that for MM1 synergy the network has a good resilient response to reductions in production enterprises. When dealing with MM3 synergy, the operating costs descend as production becomes smaller, until it becomes zero for a zero production output case, figure 5. Both latitude and resistance of the network stay constant up to 80% of the production reduction. At that point both fall to zero, reducing substantially the range between costs and therefore raising the slope of the graph. Hence, the network will be resilient during the analysis until the product supply is reduced by 70%. At that moment the resilience of the network drops significantly. The decrease in production also reduces the savings caused by the implementation of MM4 synergy, reaching a critical point of profitability at 74% of reduced production both for each of the companies and for the whole system, figure 6. The network will not be resilient to drops in production larger than 74% by the companies of the system since that situation has zero latitude. For reductions of the production lower than 74% the latitude is low although it stays almost constant throughout the simulation. Resistance is also low, as the slope for the graph of the simulation scenario ($IS_{1,2}$) is small and remains constant. This leads to the conclusion that the network might be resilient for reductions lower than 74% although it is reduced as the network approaches the critical point of profitability.

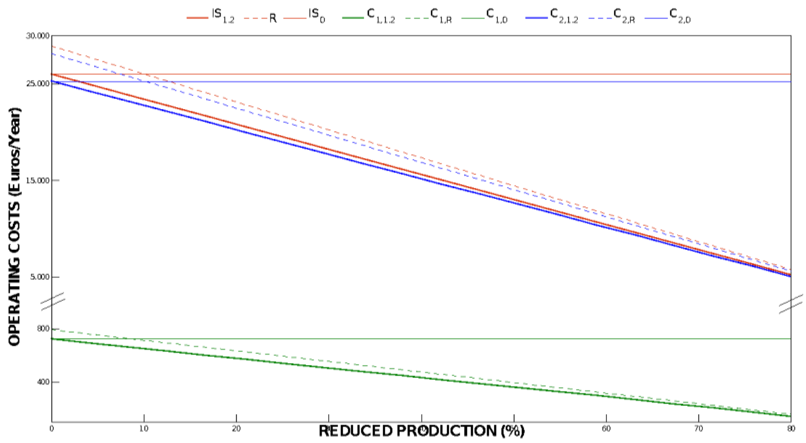

Figure 4. MM1 synergy analysis results.

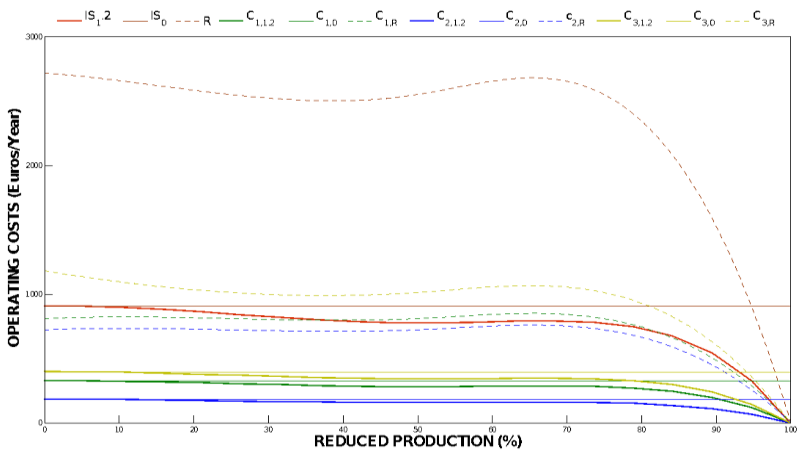

Figure 5. MM3 synergy analysis results.

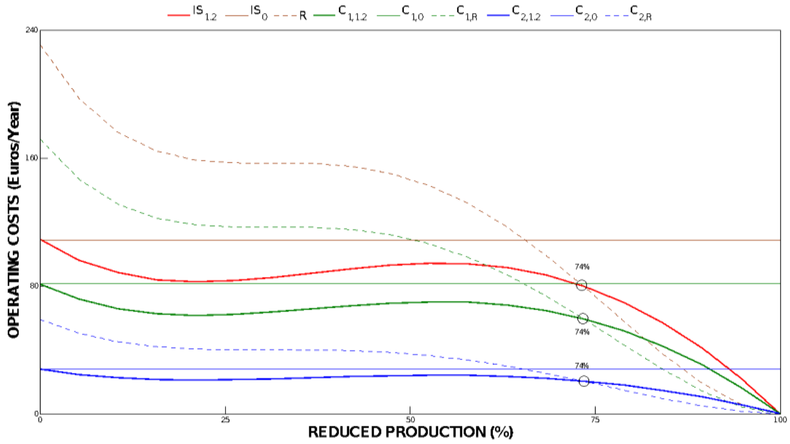

Figure 6. MM4 synergy analysis results.

6. Conclusion

This work offers an innovative methodology to see and understand the viability of industrial symbiosis synergies among companies in a better way. A preliminary technical, economic and environmental feasibility assessment is combined at the design stages with supply chain operation concepts, modelling and analysis of the potential synergy network to be implemented.

For this purpose, an industrial symbiosis supply chain model (ISSC) has been developed by looking at an industrial symbiosis network as flows transfer from the supply side of sources to the demand side of sinks where entities perform as suppliers, receivers and processes. Additionally, computational implementation allows the analysis and experimentation of the supply chain performance under different scenarios of resource supply and management. Key indicators of the supply chain performance are used with a focus on resilience assessment. This means evaluating the industrial network capacity to buffer the impacts due to several changes that might happen, such as shortage or variations of secondary resources, price fluctuations of raw material or transport route deviations among others. Based on the results shown in this work for the scenario of a decrease in production flows within the companies, a feasible IS network could be designed against possible events during operation, i.e. estimating beforehand that it would not be resilient to overall reductions in production above 74%. This inclusive understanding of industrial symbiosis performance can help to define better strategies for the design and organization of the system network, such as the agreed amount of exchanged flows between companies, and work guidelines could be inferred on how to make the network resilient to potential disruptions.

The ISSC model is suitable for industrial complexes and scalable to regions and industrial sectors. Through visual schemes and also computational outcomes, a complementary analysis to the feasibility studies of industrial symbiosis projects is offered in order to recommend and implement new configurations of sustainable supply chains. Moreover, the ISSC model has been built on the basis of being further simulated with companies' detailed process operation data so as to visualize the system over time and gain new insights to help companies make industrial symbiosis investment decisions.

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