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"By-product synergy" changes in the industrial symbiosis dynamics at the Altamira-Tampico industrial corridor: 20 Years of industrial ecology in Mexico

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ABSTRACT

The Industrial symbiosis emergence constitute a complex and dynamic process that we set in four different phases in this paper: Emergence, Regional efficiency, Regional learning, and Sustainable Industrial District. Embedded in a theoretical framework concerning the industrial symbiosis dynamic, this paper triggers a historical sequence of consequences in the industrial ecosystem evolution encompassing micro and macro elements, which also depends upon the individual actors' intervention in the network. The industrial symbiosis at Altamira is depicted here as a centralized and ancillary industrial symbiosis embedding a socio-technical and environmental model, one of the most complete biophysical, social, and economic symbiotic case studies in Latin America. The further historical analysis uses the number of actors composing the industrial network and the amount of material and energy exchange flows as a proxy for the success of the Altamira By-Products Industrial Symbiosis as a way to approach sustainability in the industrial ecosystem and attractiveness in the territory. According to the analysis of those proxies in Altamira, the actors involved in the network decrease at the Regional efficiency stage, with the highest synergies rate. The Regional learning phase follows the dynamic through an eco-innovative ecosystem strategy, encompassing small and medium size firms in the region, as the mechanisms for improving learning and innovation, decreasing transaction costs and boosting sustainability.

1. Introduction

Within the framework of industrial ecology, the study and promotion of industrial symbiosis have generated a large amount of research (Chertow, 2000; Dannequin et al., 2000; Chertow, 2007; Beaurin and Brullot, 2011; Boons et al., 2016; Diemer, 2017). Based on the concept of biophysical symbiotic exchanges, industrial symbiosis engages "separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products" (Chertow, 2000) for mutual economic and environmental benefits (Christensen, 2006). Industrial symbiosis closes loops by turning waste into valuable materials that can replace raw materials in an industrial system, to reach a natural closed ecosystem (van Berkel, 2010). More recently, Diemer and Morales (2016) have defined Industrial Symbiosis (IS) as a subfield of industrial ecology driven by "strong sustainability" expectations (Diemer, 2017). The idea that symbiosis can be a model for sustainability is based on the interaction of four pillars: eco-efficiency, cooperation, proximity, and resilience. From this viewpoint, industrial symbiosis can be presented as "the process of cooperation developed by networked actors in a common geographical, organizational, and institutional environment. Voluntary involvement of local authorities, firms and NGO must promote synergies aimed at improving eco-efficiency and resilience of the dynamic system" (Diemer, 2017).

If industrial symbiosis has often been associated with industrial process studies (material and energy flows, input/output models, life cycle analysis) or efficiency improvements, today a lot of attention is focused on the social context and the dynamics of the learning process. The connection between biophysical exchanges and social interactions has been analyzed by Sterr and Ott (2004); Gibbs and Deutz (2005); Hewes and Lyons (2008), Shi et al. (2009) and Boons and Howard-Grenville (2009). These authors prefer to highlight the social dynamics within a symbiosis, rather than the economic benefits or technological

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issues. Trust and community embeddedness, coordination mechanisms, standards, values, routines, rules, and close relationships strengthen the sustainability of the symbiosis, and give the social context of industrial ecology. These perspectives were presented at the 2011 Industrial Symbiosis Research Symposium (ISRS) in San Francisco, which was organized by the International Society of Industrial Ecology (ISIE) section of the Yale School of Forestry and Environmental Studies. The emergence of the innovative learning process introduced a new focus to industrial symbiosis studies, by considering that industrial symbiosis can be conceptualized as a process rather than a business decision. Lambert and Boons (2002) described sustainable development (of industrial parks) as "social process in which the principles of sustainable development are taken as a starting point for assessing ecological, social, and economic aspects of decisions in an integrated way through interactive learning processes among societal actors".

The aim of this paper is to explore the transition phases and the learning process of Industrial Symbiosis (IS) in order to appreciate the structural transformation in this complex system embodied by the organization strategy developed between actors and organizations in the ABP over the last 20 years. The fact that industrial symbiosis seeks to optimize the material, energy, and waste flows by acting on biophysical and economic dimensions of sustainability, should not allow us to forget that there are key social drivers which facilitate this pathway. We refer to an empirical case study, the By-Product Synergy (BPS) project at Altamira-Tampico (Mexico). We argue that IS is more than a simple group of stakeholders taking managerial decisions in a collaborative manner, the network involves the will of firms with reference to events and historical commitments. The interactive learning process documented in Altamira suggests that embeddedness in the IS can improve learning and innovation, and simultaneously decrease transaction costs and increase innovation (Patrucco, 2009).

This paper starts with a diagnosis of the ABP IS, identifying the characteristics, stakeholders, motivations, mechanisms, and the amount of symbiotic exchanges (mutualistic and substitution) that takes place. However, a static picture of the industrial ecosystem is not enough, and a historical analysis supports the study in order to clarify the dynamics of complex systems, which depends upon the interaction between micro and macro elements, and between individual actors in Altamira, considering the current situation as a historical sequence of consequences in the industrial ecosystem process. This ABP IS historical analysis uses as a proxy variable the number of actors composing the industrial network and the amount of material and energy exchange flows, as a way to approach sustainability and attractiveness in the territory.. We are convinced that historical analysis is useful, especially for complex social processes, and it provides better understanding of the system feedbacks and driver mechanisms involved in the industrial ecosystem.

Three questions serve as a guideline: What is the current diagnosis of the industrial ecosystem in which material and energy flows are produced and exchanged? How does the social transition phases of the process affect the functioning, organization, and future of the IS? What kind of strategies should be recommended to businesses or public actors to facilitate the transfer and learning process? This paper is organized in four sections. First, we provide a literature review on the dynamics of Industrial Symbiosis. Second, we present the context and the history of Industrial Symbiosis at Altamira. Third, we introduce the methodology of the case study. Fourth, we analyze the results, and discuss the industrial symbiosis dynamics at Altamira. Conclusions summarize the main results.

2. Literature review of Industrial Symbiosis Dynamics (ISD)

In a recent paper entitled "Industrial Symbiosis Dynamics and the problem of Equivalence, proposal for a Comparative Framework", Boons et al (2016) used their collective experience of collaborative research efforts in North America, Europe, and Asia to propose a theoretical framework for a comparative analysis at a global level. What they call the *problem of equivalence* reflects the difficulty of finding concepts which measure equivalent phenomena in different countries. Their research led them to consider that industrial symbiosis should be conceived as a process; a sequence of events which can be viewed as a social mechanism. This approach to industrial symbiosis dynamics tries to understand how the process of industrial symbiosis unfolds and spreads within a network of actors.

Lambert and Boons (2002) hypothesized that the process of sustainable development consists of a continuous stream of co-operative efforts through which a group of actors advance their understanding of how to assess the social, economic, and ecological aspects of their decisions in an integrated way. Ideally, if each of the co-operative efforts contributed to the progress of the group of actors towards sustainability, Lambert and Boons noted that in practice, two problems prevented the development of the process: (i) If it is relatively easy to initiate change in the short-term, social changes often revert to their old patterns. The embeddedness of a social pattern in a rigid institutional context might explain this situation, and the actors need to be involved in the changing process. (ii) Change is often incremental and is more linked to system optimization than to system change, so it is important to find the leverage points capable of balancing the existing system. For Lambert and Boons, industrial symbiosis offers an opportunity to implement these insights. Only a few elements drive the system: (1) The goal is not only to reach environmental targets, it is also necessary to improve the social, ecological, and economic dimensions of sustainability (Diemer, 2012). (2) If continuous appraisal of the system is important, a strategic vision for operational implementation is essential. We could summarize this idea by the phrase "think global, act local" commonly used in the jargon of sustainability. (3) There is a need to connect social and technological issues. Trust, commitment, collaboration, and communication must be compatible with technological frontiers (each individual firm should identify and follow its own technological pathway; there is not an overall strategy for all the actors in the system). Lambert and Boons (2002) defined broad types of industrial park: 1. Mixed industrial parks, 2. Industrial complexes (where industrial symbiosis operates) which are focused on the optimization of material and energy flows, and where a connection between biophysical exchanges and social relations is a necessary but not sufficient condition for improving the dynamics of the process of symbiosis.

Boons and Berends (2001) and Baas and Boons (2004) presented an interesting theoretical perspective which shows how the emergence of industrial symbioses based on win-win situations between firms could lead to an organization strategy embracing industrial development (Diemer, 2017). Their analytical framework begins with a static approach to system boundaries (sector of industry, product chain, and regional industrial system) and focuses on changes that influence the system. As regards change, the authors argue that a regional system "may be forced to grow in terms of activity numbers and actor's diversity". Life cycle (network change), learning network, collective facilities outsourcing, community development, and innovations justify the adoption of changes, which follow the three following stages. The first stage, *regional efficiency*, describe an autonomous decision-making phase triggered by firms that includes coordination with local stakeholders to decrease inefficiencies (e.g. utility sharing). The second stage, *regional learning*, is based on mutual recognition and trust: firms and other partners exchange knowledge and broaden the definition of sustainability on which they act. The third stage, *sustainable industrial district*, shows change towards a strategic vision and collaborative action rooted in sustainability[1].

This analytical framework helps to analyze regional industrial system (Boons, 2008) cases, and to explain the different alternatives to

[1] Chertow (2007) notes that it is not clear that the third stage, sustainable industrial district, will happen soon, or if a collective orientation will ever fully fit with the other imperatives of firms.

closed loops (central planning, governmental agencies, or self-organization market), without disregarding the structure, function, and changes in the regional industry. Ashton (2009) combined insights from industrial ecology and economic geography with complex system theory to identify external forces and interactions between different actors. He also introduced economic geography to examine the reasons for the concentration of industries in certain regions, the organizational dynamics between businesses, and the advantages for companies and people. Using Porter's typology (1990), he outlines four sets of forces which drive the success of a region: (1) *company strategy, structure and rivalry*; (2) local market demands; (3) *the availability of factors of production and*; (4) *the existence of related industries and institutions that support the core industries*. The organizational structure of the regional industry results from these economic forces, but also from social forces that define the acceptable standards and practices. Complex system theory is useful to look at interactions between actors at multiple levels and to examine how these interactions shape and change system structure and function (Holling, 1987, 2001). Ashton considers that a regional industrial ecosystem may be conceptualized as a complex adaptive system with diverse self-organized subsystems (including firms at one level and managers at another), with multiple connections between them, and the ability to learn and adapt to external or internal changes. The changes in the industrial symbiosis are conceptualized as an adaptive cycle of a complex system, and resilience is a key factor to fight against perturbations and disturbances. This framework is interesting but we have identified two limits:

(1) To study the changes in industrial symbiosis does not mean representing its dynamics. It is necessary to use another form of complexity, a methodology introduced by Forrester (1961), *Industrial Dynamics*. System Dynamics uses the concepts of information feedback and state variables to model social systems and to explore the link between system structure and behavior changes over time (Forrester, 1968). To model the dynamic behavior of a system, Forrester (1969) identified four structural features: (i) Closed boundary around the system; (ii) Feedback loops as the basic structural elements within the boundary; (iii) Level (state) variables representing accumulations within the feedback loops; (iv) Rate (flow) variables representing activity within the feedback loops. The purpose of the system model is to explain behavior by providing a causal theory, and then to use that theory as the basis for designing interventions in the system's structure, to attempt to change behavior and improve performance (Lane, 2008). Thus, the evolution of industrial symbiosis may influence the reinforcing or balancing loops in the system (Sterman, 2000; Coehlo et al., 2017).
(2) Because resilience is a feature of a system of ecological and economical interactions, Ashton (2009) used the first definition of resilience. This definition refers to stability close to equilibrium, resistance to disturbance, and time taken by a system to return to equilibrium, Holling and Meffe, (1996), called it "Engineering resilience". There is a second definition of resilience, which highlights conditions far away from equilibrium. Instabilities can move the system towards another behavioral regime, that is, into a different state of stability (Holling, 1973). Thus, resilience is measured by the maximum intensity of disturbances the system can absorb without changing structure, behavior, or regulatory process. Holling refers to this as "ecological resilience". This last definition implies analyzing the maximum disturbance one symbiosis can accept without changing its operating system or organizational structure. For us, it is a pillar of strong sustainability (no substitution between natural capital and artificial capital), which reinforces the concept of industrial district.

More recently, (Boons et al., 2011) conceptualized industrial symbiosis as a process. Even if that description changed afterwards (Boons et al., 2016) we consider it relevant for our study, because the dynamic is analyzed in two levels. At the first level, they insisted on the proximity of industrial relationships (Jensen et al., 2018). They used the concept of Regional Industrial System (RIS) defined as "a stable collection of firms located in proximity to one another, where firms in principle can develop social and material/energy connections because of that proximity". Local authorities and other actors (consumers, citizens, NGOs, etc.) can get involved in the symbiosis project and increase the viability of the regional industrial system. Industrial symbiosis is connected to eco-industrial parks or industrial clusters (Patnaik and Poyyamoli, 2015) It was pointed out that, although geographic proximity is important for industrial symbiosis (Ehrenfeld, Chertow, 2002), it is not the only condition for resource exchanges (Wu et al., 2016). The industrial success also depends on the trust and the social network developed by the agents' community. Boons et al., (2011) introduced the concept of *institutional capacity building*, developed by Innes and Booher (1999); institutional capacity building is "*an array of practices in which stakeholders, representing different interests, come together for face to face, long term dialogue to address a common concern issue*". Three forms of institutional capital may reinforce the industrial symbiosis: (i) knowledge and innovative resources (internal and external), (ii) relational resources (embeddedness of agents in social networks), (iii) mobilization capacity (structure and means to induce knowledge resources and relational resources).

At the second level, they tried to understand how industrial symbiosis spreads in society, this dissemination is the result of the transmission of innovation and its underpinning effect in the social context, which highlights the ability of the system to adapt to its environment and at the same time change its environment. Boons et al. (2011) proposed a list of transmission mechanisms that are responsible for the diffusion of industrial symbiosis related to a transitional process: constraint, imitation, governance of private interests, public initiatives, formal and informal training, and altering the boundaries.

These mechanisms seem to play a key role in the conception and the diffusion of industrial symbiosis; they open a very large field of research into the historical transition of socio-relational, organizational, and cultural issues. Firstly, these mechanisms may update the definition of industrial symbiosis in a social approach (Lombardi, Laybourn, 2012) by stating, "Industrial symbiosis as a transitional process of industrial organization in a network to foster innovation and long-term cultural change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes". Organizational sociology examines how social forces drive structures and force the interactions between groups (Scott, 2004). Studies in organizational sociology are focused on how shared beliefs, values, and standards develop a social system and how these, in turn, influence the organization's behavior and function. The industrial ecosystem may constitute a new organizational field, where new standards will emerge, including communication structures between different industries, for example, by considering traditional wastes as potential raw materials through the institutionalization of mechanisms for collaborative resource management (Jacobsen, 2005). Social structure patterns induce repeated interaction between actors, usually symbolized as networks, where nodes and ties represent actors' interdependent connections (Ashton, 2008).

Secondly, these mechanisms detailed in Table 1 may help us to build a description of the dynamics of industrial symbiosis, showing the initial actors, the actors' motivation, the history, and typical outcomes. (Boons et al., 2016) list seven categories that could generate a symbiotic network: self-organization, organizational boundary change, facilitation/brokerage, facilitation of collective learning, piloting of facilitation and dissemination, government planning and innovative platform

Table 1
Seven types of industrial symbiosis dynamics.
Source: Boons et al., (2016)

Dynamics Typology	Initial actor(s)	Motivation of the initial actor(s)	Following actions/overall storyline	Typical outcomes
Self-organization	Industrial actor	Economic and/or environmental benefits from IS	Industrial actors expect benefits in developing symbiotic linkages→ industrial actors search for suitable partners (existing partners in vicinity or new partners attracted from further away) → after finding a suitable partner, contracts are negotiated→ linkage becomes operative→ [repeat]	Agglomeration Hub-and-spoke network Decentralized network
Organizational boundary change	Industrial actor	Eco-efficiency and business strategy	An industrial actor expands its activities through vertical integration and develops internal exchanges→ the industrial actor changes its strategy from vertical integration into outsourcing→ the linkages remain and the system evolves into an inter-organizational network	
Facilitation/ brokerage	A public or private third-party organization	Enable firms to develop tacit knowledge and exchange experiences	A facilitator picks up the concept of industrial symbiosis from existing examples → the concept is translated into specific regional context→ industrial actor and facilitator engage in collaborative learning to develop symbiotic networks.	One-off network of symbiotic exchanges
Facilitation of collective learning	A public or private third-party organization	Enable firms to develop tacit knowledge and exchange experiences.	A facilitator picks up the concept of industrial symbiosis from existing examples → the concept is translated into specific regional context→ industrial actor and facilitator engage in collaborative learning to develop symbiotic network	
Pilot facilitation and dissemination	A public or private third-party organization	Learn from non-local existing IS cases and experiment in a local context	A facilitator picks up the concept of industrial symbiosis from existing examples → the concept is translated into specific national/regional context→ groups of co-located industrial actors are selected to serve as exemplary cases→ further refinement of the concept occurs through learning in pilot projects→ the experiences from pilot projects are transmitted by the facilitator.	Diffusion of IS concept among networks
Government planning	Governmental actor(s)	Learn from existing IS cases and implement	A governmental actor picks up the concept of industrial symbiosis from existing examples → the concept is included in policies and translated to the specific national/regional context→ the governmental actor develops a plan for the development of linkages through stimulating and/or enforcing policy instruments→ the progress of implementation is monitored→ the results of evaluations are fed back into the policy to realize continuation/renewal/closure	
Eco-cluster development	Governmental and/or industrial actors	Innovation, economic development	Local governments and/or industrial actors develop a strategy for the development of an innovative platform→ symbiotic linkages are developed through participatory process among multiple stakeholders as part of the broader eco-innovative strategies.	Redevelopment Brownfield development Greenfield development Innovation cluster

development, categories that we use to analyze the historical transitional process of industrial symbiosis emergence in the sought of a resilient complex system.

Every category has its own dynamic. For example, the dynamic of self-organization describes the development of symbiotic activities due to the self-motivated strategies of industrial actors. These actions are driven by individual industrial actors and occur within an institutional context (level of trust, social standards, regulation policy, etc). Kalundborg and its 40 years of improving synergies, is a good example. The dynamic of innovative platform development describes cases where different local actors (local government, firms, and interested organizations) come together around the goal of achieving economic development and/or technological innovation, and IS is implemented as part of that developmental strategy (Boons et al., 2016). An integrative transitional process seems essential to resolve any problems or conflicts between actors and to engage them in an industrial symbiosis.

Taddeo et al. (2017) compared the dynamics of industrial symbiosis and the main characteristics of (regional) industrial systems over three case studies (chemical, automotive, and agri-food industries) located in the Italian Region of Abruzzo. The authors considered that the most significant factors influencing the development of industrial symbiosis arise from different life-cycle stages. The design of the framework refers to three stages: (i) structural factors; (ii) factors and forces embedded in people and organizations: culture, experience, knowledge, roles, rules, routines); (iii) future expectations. From the three previous cases studied, the structural factors that play the most relevant role in the industrial symbiosis are: (1) proximity of production plants; (2) infrastructure, utility, and services availability; (3) the wastes' volume and homogeneity; (4) the limited presence of hazardous materials and (5) homogeneity/heterogeneity of industries (number of industries and processes involved in the industrial symbiosis. Considering the people embedded forces we count (1) the willingness of companies and stakeholders, (2) active participation of stakeholders (local governments, agencies, key actors, local communities) and (3) regulatory system (environmental legislation and standards) (Taddeo et al., 2017).

To conclude this section, the dynamics of industrial symbiosis reviewed in this paper attempts to extend the works of Baas and Boons (2004), Boons and Howard-Grenville 2009; Boons et al. (2011, 2016) and Taddeo et al. (2017) identifying stages of construction, types of actors, and motivations in the industrial symbiosis.

The stages that we present as a conceptual framework are those proposed by Baas and Boons (2004): Regional efficiency, Regional learning and Sustainability of industrial districts, supported by the evidence we found in Altamira BPS IS. The typology has been adapted including an extra phase before Regional efficiency, called Emergence. We sought to re-embed biophysical exchanges (stocks and flows of materials and energy) in the social system (Diemer, 2012, 2017). The *Social Embeddedness of Industrial Symbiosis* (Boons and Howard-Grenville, 2009) may be useful to address some key questions addressed in this study, as: What is the current diagnosis of the industrial ecosystem in which material and energy flows are produced and exchanged? How does the social transition of the process affect the functioning, organization, and perspective of the IS? What kind of organizational strategies should be recommend to businesses or public actors to facilitate the learning process? We believe that social mechanisms introduced by Boons et al. (2016) to provide a typology of Industrial Symbiosis Dynamics could be helpful to illuminate our comprehensive overview of the Industrial Symbiosis (IS) process, offering an historical appreciative analysis of its evolution.

3. Case study context and history

Kalundborg (Denmark), which started in the 1960′s, as the success story of industrial symbiosis (Branson, 2016; Jacobsen, 2006). Other industrial symbiosis projects emerged in the 1990′s like the By-Product Synergy (BPS) project in Altamira (Mexico) started in 1997 by the Business Council for Sustainable Development at the Gulf of Mexico (BCSDGM[2]). Mangan and Olivetti (2010) argue that BPS is the matching of undervalued waste or by-product streams from one facility with potential users in another facility, to create new revenues or savings with potential social and environmental benefits. The BPS process aims to provide manufacturing facilities with opportunities to reduce pollution, and save money and energy, by working with other plants, companies and communities to reuse and recycle waste materials.

3.1. Altamira industrial district's preconditions for IS emergence

The Altamira port in the state of Tamaulipas is one of the most important coastal industrial zones in the Gulf of Mexico. It has more than 30 companies with international links to more than 55 countries worldwide. The largest businesses, which lead the region's economy, as presented in Fig. 1, are the Madero Refinery, Altamira Industrial Park, the Altamira Industrial Port, the Petrochemical corridor, and the Industrial Association of Southern Tamaulipas (AISTAC). For Altamira, the goal of the BPS project was "to promote joint commercial development among economic sectors so that one industry's wastes became another industry's input" (Young and Baker Hurtado, 1999). Promoted by the BCSDGM the Altamira BPS project aimed, in its early stages, to identify a minimum of five synergies, foster greater understanding of eco-efficiency, and create a new community of companies fostering the industrial leadership.

The Altamira Industrial Park is the strategic industrial hub in the region. The cost/benefit rationale overwhelmingly favors large-scale production companies and long-term investment. Approximately 500 ha facilitate basic services, such as water, electricity, gas and roadways. The Altamira Industrial Park has 20 big corporations (BASF Mexicana, Biofilm, Flex America, Absormex, Dypack, la Esperanza, Fletes Marroquin, MASISA, Iberdrola, Kaltex Fibers, Mexichem, Polioles, Posco Mexico, Sabic Innovative Plastics Mexico).

The Madero Refinery is essential in the area, with an annual capacity of 7.5 million tons of crude oil and refined products. The refinery consists of catalytic gasoline desulfurization plants, amine regeneration units, and utilities. The Altamira refinery was modernized in the IS emergence phase (1997–2006) aiming to reduce air and liquid emissions, as same as surface water consumption. This helped to meet an increasing regional demand for unleaded gasoline to meet Mexican environmental regulations, and assisted Mexico's electricity supply sector by shifting consumption to natural gas, increasing light fuel production, and expanding refining capacity. The EX-IM bank in the United States supported the project.

Altamira Industrial Port was built in 1980, its strategic location, only 500 km from the US border, as well as the proximity to the main economic centers in Mexico, allows for speedy access to any markets in the world letting the development of a petrochemical cluster. This cluster state the emergence necessary conditions for the BPS Industrial symbiosis, in part, because of its huge potential, carrying more than 6 million tons of cargo transit through the port every year, even though it only uses 30% of its capacity.

The previous conditions that let the Industrial symbiosis emergence in the Altamira Petrochemical Corridor in 1997, started over the attraction of several multinational corporations that represent nearly 25% of private petrochemical industry in Mexico, and produce nearly 60% of exports in basic petrochemical products (CRYOINFRA, INDELPRO, M&G Polimeros Mexico, Chemtura, McMillan, DUPONT, DYNASOL, CABOT, Enertek, and Petrotemex). The strategic decision that drives to

[2] From Mangan and Olivetti (2010), the BCSDGM was subsequently established in 1993, comprising a non-profit organization of business leaders sharing the belief that a business's success is measured increasingly by its contribution to economic, social, and environmental sustainability.

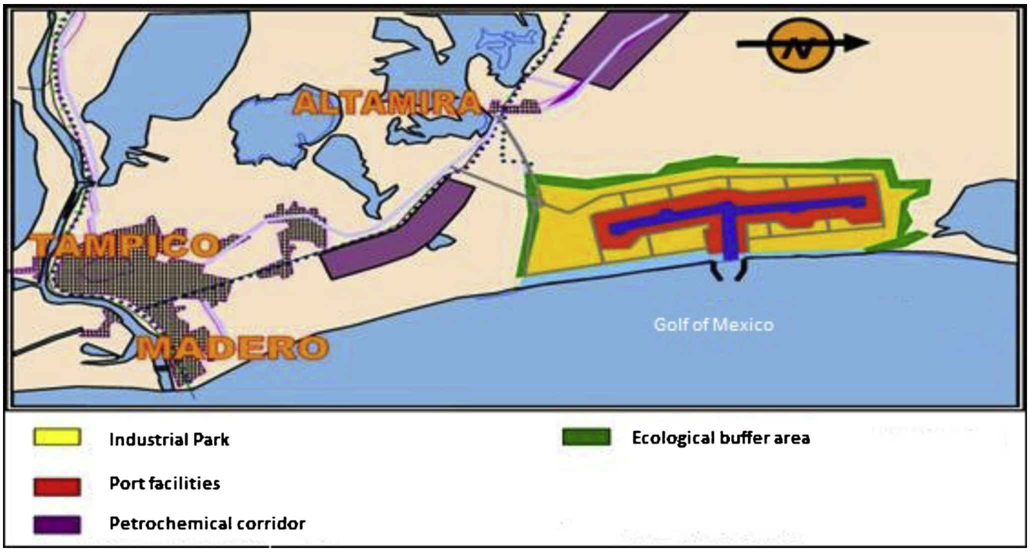

Fig. 1. Location of the Altamira Industrial Petrochemical corridor.
Source: Altamira Industrial Port (2005)

the petrochemical corridor emergence was the establishment in 1970´s of Dupont, PETROCEL, and Hules Mexicanos, stimulated by the construction of the Altamira trading port.

Another previous chunk in the IS preconditions gathering was the Southern Industrial Association of Tamaulipas (AISTAC) creation in the 1980´s, which represents some of the largest companies of the South of Tamaulipas state area and acts as a link between industry, community, and local authorities. Strongly determinant in the emergence of the Regional Industrial System and the further Industrial symbiosis in the region.

As pointed out by Frosch and Gallopoulos, 1989), even if the analogy between industrial and biological ecosystems is not perfect, much could be gained if the industrial system emulated the best characteristics of the biological ecosystem. Altamira's industrial symbiosis is still far away from an optimal and sustainable circular behavior of material and energy in the petrochemical industry. However, they are already looking for alternative processes and materials replacing the non-renewable inputs (i.e. the bio-sourced materials), through a recovery and recycling strategy. The economic, social, and environmental benefits implemented until now, are still limited according to some analyses.

3.2. Historical outline at BPS Altamira - phases and typologies

We base the historical understanding of industrial symbiosis in an integrative biophysical, social, and economic dimensions that are approached as a complex system with four different phases and typologies, as shown in Table 2.

For BPS Altamira, phase 1, the "Emergence phase" (1997–2006), was linked to the starting point of the By-Product Synergy (BPS) Project described in the Industrial Symbiosis typology as "Facilitator / brokerage" (Boons et al., 2016), because at that moment most key petrochemical companies in the area were associated with, or members of, AISTAC. Of the 21 companies that participated in this project, 18 were members. The motivation of the stakeholders was the tipping point for organizational improvements and synergy developments between firms. The BPS project presented a potential opportunity, mainly because of the geographical proximity. The existence of the AISTAC with more than 20 years of experience, the common environmental concerns shared by the companies, the collective interest to identify cleaner and more efficient processes, and the leadership of some businessmen, was a key factor to push the industrial district to a high quality and cost reduction processes, and into looking for collaborative efficiency improvements. In phase 1, the BPS project identified 373 material flows, the atmosphere of trust provide confidence, and enthusiasm was generated to cooperate in the project. Of the output flows, 120 were wastes from 78 different materials, and 54 were final products, semi-finished products, and by-products. Wastewater, CO_2, and CO were the largest amounts with 44,820, 44,400 and 26,720 ton/year respectively (Carrillo, 2007). In the first stage, the WBCSD-GM did not go into the detail of the social dimension, even when the key role of firms was clear in the industrial symbiosis emergence.

Phase 2 is the Regional efficiency (2007–2010) of industrial symbiosis, a "Facilitator/brokerage" type of industrial symbiosis almost without changes, except the fact that the main motivation of initial actors was eco-efficiency instead of transparency, and a willingness for coordination of inter-firm cooperation. This phase was characterized by the participation of 18 founding firms (members of the AISTAC), the research and education institutions Analysis and Socioeconomic Management Organization (AGSEO) at the Metropolitan Autonomous University, and the Industrial Ecology Research group (GIEI) at the National Polytechnic Institute. The supporting role of the educational and research institutes enabled an increase in the number of synergistic exchanges in the IS project, and fostered the innovation, technological, communication, and organizational skills necessary to improve the performance of the network. In this phase, the main outcome was the industrial metabolism analysis developed in the Altamira group, identifying 29 material flows, together with 63 potential symbiotic exchanges. After a technical and economic viability study only 13 of these proposed exchanges were undertaken, resulting in savings of 44,820 tons of wastewater, 44,400 tons of carbon dioxide, and 26,720 tons of carbon monoxide a year (Carrillo, 2007); (Young and Baker Hurtado, 1999). Other sources of change were the regulation pressures implemented by public agencies, and other institutions that developed Mexico's environmental policy, and the adoption of stringent environmental strategies. Some of the research questions formulated during this period concern: Which factors assure the endurance of a by-product strategy? What kind of firm can participate in a symbiosis strategy? What are the current firms' incentives to join this material and energy synergy?

The Regional learning (2011–2015) is considered the Phase 3, where the evidence suggested a turning point in the industrial symbiosis typology "Facilitation of collective learning", in which 6 of the firms became engaged in a collaborative learning process to develop a more symbiotic network dealing with the 2 main problems in the search for sustainability. First, firms discovered that it is relatively easy to achieve superficial, short-term social change, but social actors tend to

Table 2
Four phases of change at BPS Altamira, characterized by typology, motivations, initial actors and overall history.

Dynamic Phase	IS type	Motivations	Initial actors	Overall storyline and outcomes
Emergence (1997-2006)	Facilitator - brokerage	Benefit from economies of specialization. Vertical integration of production. Coordination strategies enhancement Interfirms cooperation and empowerment of the platform.	Business Council for Sustainable Development for the Gulf of Mexico (BCSDGM)	- The early stages - 21 companies engaged in the project identifying 373 potential material flows: 199 inputs and 174 outputs.
Regional efficiency (2007-2010)	Facilitator collective learning	Eco-efficiency & clean technology Environmentally friendly practices Central coordination of the IS by the AISTAC Environmental risk control Energy and material flow management	The BPS 21 firms at Altamira project and the AISTAC	- 63 more potential synergies identified by the research groups and stakeholders. -Inclusion of the research community and relevant role from public regulations.
Regional learning (2011-2015)	Facilitator collective learning	Resilience The vertical and horizontal integration in the industrial ecosystem. Composition of integrative networks between collaborative and complementary partners	The six most engaged firms in the BPS Altamira project and the AISTAC	-Decreasing number of potential biophysical exchanges to 250 and in the value of these transactions. - Industrial symbiosis members attend the number of 6 limited to ancillary products and not related to core activities and processes.
Sustainability of industrial district (2016 up to now)	Innovative platform	Adaptability and flexibility in the sought of sustainability Innovative platforms Structural and dynamic understanding of the industrial symbiosis' architecture	BPS Altamira current members, AISTAC, external participants and local authorities	- 310 potential biophysical synergies in the IS -Altamira government contribute necessary to attain 15 members thanks to a strategy for the development of an innovative platform with a broader scope of firms including small and medium firms.

fall back into their old patterns of behavior over the long term due to their embeddedness in an institutional context. Second, firms agree that to ensure system's structural resilience rather than system's optimization, the changes need to emerge from the current system. Thus, every stakeholder needs to be involved in the change process, a role that was performed by AISTAC (as a facilitator on inter-firm negotiations and agreements). The self-adaptive change process has led to a dynamic resilient state, facilitated by AISTAC. The material flow synergies were reduced to 241 to permit the determination of the conditions for establishing a resilient industrial symbiosis, because the main motivation in the Industrial symbiosis in this phase was the resilience of the system. Even with a reduced number of synergies (in volume and transaction value), the diversity of activities and actors involved in the BPS network improved the resilience in the network. A change toward sustainability at that moment was difficult to achieve in the Altamira petrochemical BPS due to the actors' divergence of interests, competing technologies, and by-products, which made synergies particularly difficult. The fact that Altamira's synergies was restricted mainly to ancillary processes was evidence of the difficulty of industrial symbiosis, as supported by the examples like the Rotterdam IS analysis of Baas and Boons (2004).

The current phase (2016 on), is being implemented, with the commitment of 15 firms and new participants in the network, even if they do not belong to the AISTAC. The decision was between maintaining a shrinking Regional learning or to try to create an over-arching industrial symbiosis framework called Sustainability of Industrial District (2016). This choice depends on managerial decisions and the willingness of the stakeholders to extend the scope of the ISN to a larger scale (local or regional) through the innovative platform development, encouraged by a decline in the volume and transaction value of synergies, partially attributed to the decreasing marginal efficiency of environmental actions, as detailed by Boiral (2005). Even if adaptability and flexibility motivation are collectively expected in phase 4, the ISN cannot be restricted to biophysical flows (313 material flow synergies) because of the complex and interconnected dimension that industrial symbiosis brings to the social dimensions of the industrial ecosystem. In this phase, the importance of social dimensions and qualitative data is undeniable. The contribution of Altamira municipal government is necessary to develop a strategy for the development of an innovative platform with a broader range of firms, including small and medium sized firms as potential stakeholders of the industrial ecosystem.

Even when we do not have the disaggregated data of every firm from the Altamira IS available, we include as complementary sources the historical analysis developed by the authors in previous research studies. The historical understanding of this studies let us integrate to the analysis relevant parameters as the number of stakeholders involved in the IS, the potential material flows synergies and the total amount of companies involved in the network. In despite of the aggregation of this information it help us to build the argument on the dynamic construction process of the industrial symbiosis and the resilient behavior over time.

4. A dynamic methodology for industrial symbiosis analysis

The methodological approach adopted can be defined as "appreciative theorizing" (Nelson, 1994, 1998). Appreciative theorizing is appropriate in the analysis of organizational strategies in the industrial ecosystem because of the high level of social embeddedness of the collective process, where interaction and evolutionary processes cannot be fully captured by formal models and may often be expressed only in qualitative terms. As Nelson put it:

Appreciative theorizing tends to be close to empirical work and provides both interpretation and guidance for further exploration. Mostly expressed verbally, triggering the articulation of what we think is going on. However, appreciative theory is very much an abstract body of reasoning. Certain variables and relationships are treated as important, and others are ignored. There generally is explicit causal argument. On the other hand, appreciative theorizing tends to stay quite close to the empirical substance. (1994: 500)

In this spirit, the paper proceeds with an analytical interpretation of the evolution of the industrial organizational process form that has coordinated symbiosis and resilience seeking in the petrochemical industry in Altamira over the last 20 years.

A set of interviews has been conducted with corporate managers, as well as with local policy makers, expert analysts and members of collective bodies knowledgeable about the process of organizational change experimented in the local petrochemical industry. This took the form of vis-a`-vis interviews with 10 interviewees. Since issues such as interactive behaviors, resilience, institutional capacity, organizational strategies and cooperation are extremely complex, open and face-to-face interviews allow capturing the very qualitative nature of such interdependences. Moreover, the organization of very close interviews with selected members of the local “petrochemical community” allows the gathering of information from collective, interactive and in-depth discussion, at the same time leaving room for unexpected issues emerging from the discussion, and in turn also strongly motivating the commitment of the participants in the research work.

To propose an appreciative understanding for the industrial symbiosis dynamics, seeking to encompass a comprehensive overview of its organizational process, we need to stress the social dynamic approach (based on the authors’ literature review, and interviews with public authorities, civil society, and research and education organizations) over the biophysical one. This methodology is applied to the Altamira Industrial Symbiosis case study, and underlines its potential application to other cases when the historical analysis of the organizational process becomes an imperative to approach the structural resilience patterns of behavior in the local industrial system.

4.1. Biophysical approach

One of the proxies concerned in this paper in order to approach the structural resilience of the industrial system is the amount of material flow synergies engages in the petrochemical district since 1997. The data gathering was based on a literature review supplied mainly by the World Business Council of Sustainable Development – Gulf of Mexico. According to this review, a material and energy flow diagram (Fig. 2) was created to improve material and energy flow accounting.

The following diagram (Fig. 2) was the only available model of BPS Altamira, and the internal process of every company was confidential. The only information shared was the waste flows used as raw materials by other companies through a synergic relationship. The material and energy flows were not explicitly described, but a symbolic language was developed at the GIEI to properly describe the Industrial Symbiosis Diagrams by Lule Chable et al. (2013). The data gathering of the regional efficiency (Phase 2) and the regional learning (Phase 3) phases was obtained from the available literature and from the field study of authors in (Cervantes and Turcott Cervantes, 2013a). All this research on the BPS Altamira project was nourished by several visits made to the AISTAC, to the main companies linked with industrial symbiosis, and to public authorities; and by the construction of Synergy Diagrams, depicting existing synergies and proposing further potential synergies.

A regional diagnostic was made with secondary sources and official data to identify the industrial dimension and AISTAC’s influence during all phases, complemented by the interviewees applied to some board directors.

4.2. Social approach

To gather the qualitative data that shed light on the social

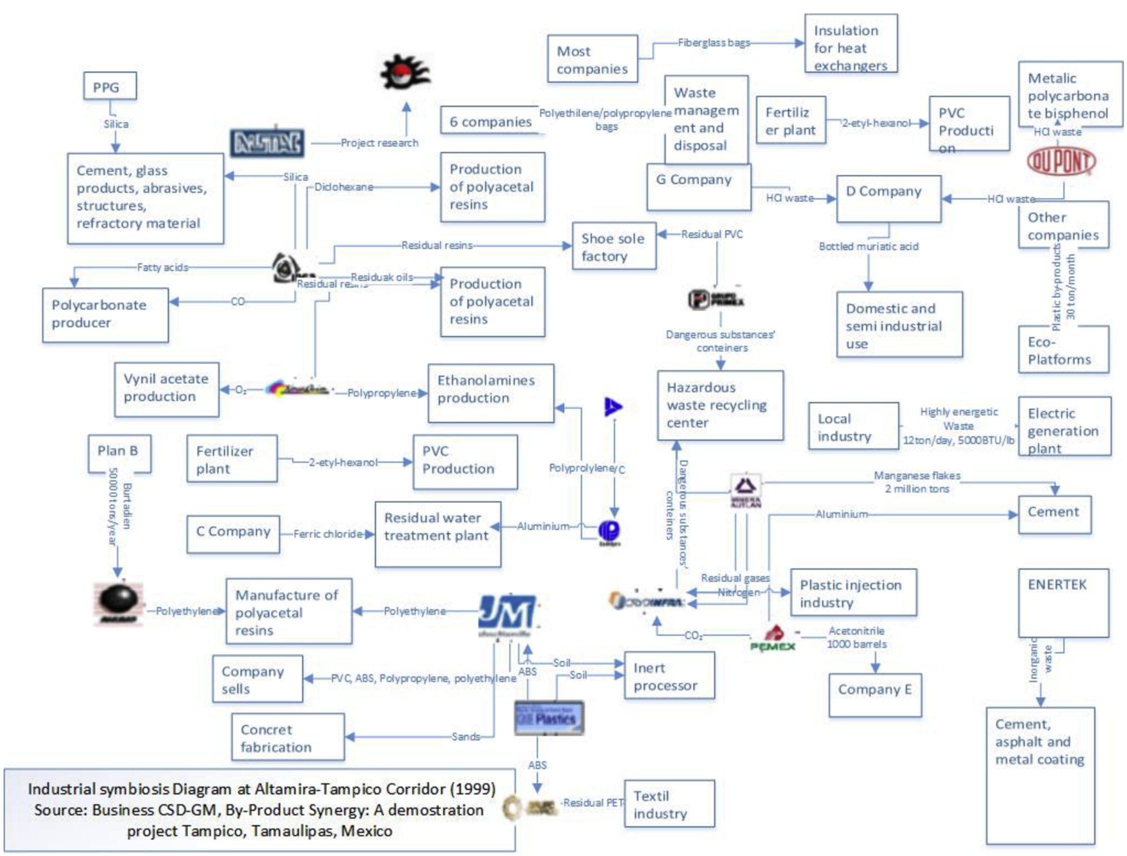

Fig. 2. Material and energy flow diagram created from information provided by the WBCSD.
Source: (Lule Chable et al., 2013)

dimension of Phase 4 of the BPS Altamira project, interviews were conducted with AISTAC key actors, firms' heads, and non-profit stakeholders involved in the industrial symbiosis.

For Phase 1, Phase 2, and Phase 3 of the industrial symbiosis dynamic, the literature review and the pH.D. dissertation of Carrillo, Graciela in 2006 provided materials to identify the social keys to the development of Industrial Symbiosis at BPS Altamira. From the interviews (February 2017) with the most engaged firms of the BPS Altamira project (CABOT, Mexichem, M&G Petroquimica Mexico, INDELPRO and INSA), we developed a better understanding of how ideological structures encompassing the biophysical and social dimension could drive firms to use a shared language which might be impossible without exploring the relevance of historical transition organizational process.

The theoretical framework proposed by Baas and Boons (2004) and the Industrial Symbiosis Dynamic typology suggested by Boons et al (2016) provide a logic for the phases of industrial symbiosis which is used as an input to this paper. Both the Baas and Boons framework and the Boons et al., typology explore the linkages between the types of dynamic that could build the transitional appreciative understanding of the BPS Altamira project, encompassing resilience and innovative learning. Without the understanding gained from looking at the history of stakeholders and regions, it could soon become the tangible example of an inarticulate structure of variables and resources, acting in the short-term and trying to solve problems on a day-to-day basis.

We are confident that the identification of motivations, key actors, key factors, and the overall IS history would expand the expected benefits from a complex dynamic understanding and would provide relevant insights for the decision makers when choosing the optimal organizational strategies, according to the phase of development of the industrial symbiosis.

5. Results and discussion

We aim to depict the benefits obtained from a comprehensive transitional process analysis for Industrial Symbiosis, defining for this purpose four different phases – emergence, regional efficiency, regional learning, and sustainable industrial district, relating them to an underpinning motivation linked to the starting actors, which interacts in the overall history of the IS. Our understanding of the industrial system depicts socio-technical and environmental collaboration in different contexts, motivations, actors, phases of development, and outcomes. A better understanding of the history clarifies the required organizational strategies and mechanisms to foster managerial skills and stakeholder's motivations to take part in a compelling interactive learning process.

In the Fig. 3, we can corroborate that when the resilience minimal requirements are not respected, the number of firms involved in the network and the number of material flows in the Industrial Symbiosis decreased over time up (Phase 3). According to the data obtained in the interviews, this effect was also triggered by the decreasing marginal efficiency of synergy investments. The previously mentioned marginal efficiency decrease reduces the attractiveness of the symbiosis, combined with the fact that the Altamira BPS Industrial Symbiosis is based only on ancillary processes in the petrochemical industry. Phase 4 is a

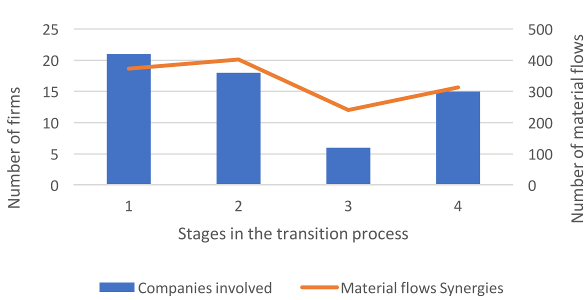

Fig. 3. Historical transition process in Industrial Symbiosis.

tipping point when the Altamira municipal government contributes to the development of a strategy for the development of an innovative platform. The innovative platform includes small and medium size firms as potential stakeholders of the eco-innovative strategies, increasing the synergy material flows concerned.

Relevant insights were developed, that let us understand the attractiveness mechanisms of industrial symbiosis, and the willingness to join the IS network for a potential firm. The mechanisms, which affect firms' willingness to join to the symbiosis project, are based on social and biophysical dimensions. In the social dimension, we found the size of the company, cost criteria, shared language (facilitating communication), organizational skills, environmental values (respect, cooperation, ethic and social responsibility), trust in relevant structures, and environmental regulation in Mexico. In the biophysical dimension, we found technical resources, available technology, and availability of by-products in the IS (Cervantes, 2013b).

5.1. AISTAC performance

The BPS Altamira project shows that corporate membership in the association incorporates environmental values, and encourages innovation and communication between members, becoming a key driver of synergy development. In the AISTAC, they have managed to involve company employees in the search for economic and environmentally efficient alternatives. A method for systematizing exchange, creating trust, and encouraging communication between environment managers was successfully created at Altamira.

5.2. Company size was a determining factor

Only large, and occasionally medium-sized companies, could make long-term investments.

5.3. Environmental values

Among the Altamira companies, market positioning and incorporation of environmental policies in their strategies make it easier to invest in current expenditure than to invest in new projects. Additionally, environmental practices are considered as ethical investments and thus well placed for funding. In any case, the image of an environmentally friendly/sustainable company is important as it leads to a more positive relationship with the community and environmental organizations.

5.4. Cost criteria

It was clear at the beginning that this economic driver would determine the implementation of the identified synergies. Companies are engaged in cost-benefit analysis and market studies to determine the viability of the synergies, because they can obtain resources if it is cost-effective. The companies realized that after the project everybody would get the expected profits, meet investment return targets, and obtain the economic and environmental benefits.

5.5. Technical resources, available technology, and by-products

It was found during the project that most of the identified by-products, as well as the needed technologies, were available, and that firms relied on the by-products properties for transformation and reuse. If the participants were not familiar with the technology, specialists were invited to explain specific processes. However, synergies were achieved where the technology permitted participants to move forward in a modernization process or technological adaptation. Projects failed because their byproducts did not match the required technical specifications.

5.6. Organizational skills

Time availability was identified as an important barrier because of the demands of the work day and higher priority tasks in the company. Despite this, the AISTAC's role in coordination and organization was valuable.

5.7. Environmental policies and regulations in Mexico

These were the largest obstacles to synergy consolidation, because of the autocratic and centralized legislation system. In Mexico, instead of an environmental policy that encourages the existing collaborative examples of synergy, a broad legal framework exists and regulates the economical agents' actions. It has thus become more and more difficult to comply with the law. This was not the case for large companies. Because they are big, they are very visible, so usually their internal environmental policy strictly follows the legislation. Laws, permits, and procedures in energy, handling, use, and disposal of residue transportation and recycling have become a serious obstacle for innovation in medium, small or micro enterprises in Mexico.

The appreciative methodology considers the Industrial Symbiosis as a process for organizational innovation in the industry, as a complex interdependent system. To imagine a resilient industry, we need to go beyond input and output flows (the study of process), to get into and reconnect sub-ecosystems. We need to look for broader scopes to reconnect the different sub-systems by studying their interactions and the possibilities for producing symbiosis, and this re-connection could be motivated by the key mechanisms for IS success. The production process as we know it today is a problem, so we need to think about closing larger loops (in water, energy, material, infrastructure, and non-material resources between housing, labor, energy, health, transport, population, and industrial sub-systems).

Industrial Symbiosis challenges us to think about altering structures in the industrial system. This change has been achieved by considering relevant insights such as different organization patterns, which are not necessarily new if we look back in history, for example the collaborative/cooperative social structure. This kind of structure could help to achieve a better understanding of the social innovation and transition process, its underpinning motivations, mechanisms, actors, and typology.

6. Conclusion

While Industrial Symbiosis may not, be a perfect model (e.g. Kalundborg), it can be an ecosystem in which inter-relationships result in cooperative actions alongside competition, and in which biophysical and social dimensions improve the characteristics of a local industrial ecosystem. This historical analysis and description of the symbiotic trajectory, taking into account social and economic aspects of the Tampico-Altamira experience shows that a petrochemical industrial ecosystem, which builds symbiosis around ancillary processes and which is based on a few central firms, achieves decreasing efficiency in the synergies investments if the network resilience is not taken into account.

According to the historical analysis, some innovative strategies could be proposed to foster attractiveness and by-product exchange resilience, like an innovative ecosystem strategy, encompassing small and medium size firms for territorial engagement. The empowerment of new startups opens new business opportunities in information technology, logistics, alternative energy, smart cities, etc., where successful mechanisms are shifting paradigms, improving learning and innovation, decreasing transaction costs, and increasing flexibility, influencing positively the industrial ecosystem.

We consider that an historical analysis of the industrial symbiosis process is useful, especially because they stress the social relevance in the processes (inter-firm, intra-firm, and territorial). This kind of systemic and dynamic analysis provides a better understanding of the feedbacks and driver mechanisms, the firm participation/membership, the values and the communication skills involved in the industrial ecosystem. This analysis could be replicated in other industrial symbiosis networks, and become a resilience paradigm for a new business model, encompassing a kind of socio-ecological strategy, which has the potential to reduce the ecological impact of the industrial processes of large corporations.

Conflict of interests

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Author contributions

All the authors contributed substantially to the research presented in this paper. Gemma Cervantes and Manuel Morales conceived of and designed the research and methodology. Arnaud Diemer contributed to the research with the idea of the evolving phases at the industrial symbiosis in Altamira to depict the dynamic features, and he also contributed with relevant insights for the conclusion. Graciela Carrillo proposed the Industrial Symbiosis framework at Tampico-Altamira case study, including the information about the successful key factors in this case.

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