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CombiningEfficiency and Resilience Assessments in Industrial Symbiosis Value Chains: A Comprehensive Flow Analysis

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ABSTRACT:
The viability of firms that participate in industrial symbiosis (IS)is influenced by the impact that by-product synergies have on the economic efficiency and resilience of those firms in the IS network. Systems theory, industrial ecology, and value chain dynamics constitute the necessary frameworks to analyzethe viability of IS value chains through efficiency and resilience assessments. Using Mexico's Altamira Industrial Port as a case study, we identify and describe three IS value chains A, B and C and build variables to measure viability through efficiency and resilience. We find that only the three participating firms in value chain B are both sufficiently efficient and resilient to constitute viability. Moreover, these three firms (CABOT, INSA, and CHEMTURA) represent an anchor in port's/network's IS viability through the integration of aresilience and efficiency analysis by value chain.The study attempts to get an improved systemic understanding of IS value chain viability if resilience is aggregated to the efficiency analysis of by-product synergic exchanges of each firm involved in the IS. Finally, we recommend applying modular assessments on efficiency and resilience to firms participating in IS value chains, because according to the size and length of stressors influencing the IS dynamics, different actions should be implemented in the industrial ecosystem to anticipate potential scenarios where short-term, long-term, and structural stressors will endanger the viability of the IS network/value chain.
Keywords:*viability, efficiency, resilience, value chains, systems*

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I. INTRODUCTION

Theconcept of industrial ecology (IE) entails a comprehensive and systemic relationship with the biosphere usingthemetaphor of ecological systems dynamics(Erkman, 1997). In this metaphor, industry is a semi-closed ecosystem where actors seek to close, extend, or intensify material and energy loops to make economically appealing reductions of the environmental impact of industries (Ayres & Ayres, 2002). Industrial ecosystem actorsinclude extractors, producers, transporters, consumers, suppliers, and de-composers who exchange material and energy between themselves and the environment. The European Commission recommends the adoption of IS, recognizing its key role in supporting eco-efficiency and sustainable development (European Commission, 2011, 2015). As a result, policymakers of many countries have promotedindustrial symbiosisaround the world since the beginning of the 20th century.

The IS strategy relies on synergic exchanges and sharing in the field of IE, aiming to enhance industrial viability through comprehensive consideration of energy and material flows. In this paper,we aim to integrate an assessment of resilience into/the standard measure of IS efficiencyto gain a better understandingof the mechanisms needed to achieve supply chain viability (Ivanov, 2020), exploring the resilience of industrial ecosystems through the diversity of their by-products and the redundancy of waste producers and users within the ecosystem's value chains. In Latin America we can find a relatively small but compelling set of IS examples in the scientific literature.The agricultural symbiosis/social and ecological agro-industry model, GERIPA,described by Ometto, Ramos, & Lombardi (2007), and a biorefinery case study by Santos & Magrini (2018), both in Brazil, are among the most representative/are among the best examples.

The literature has identified twomain challenges in the achievement of IS supply chain viability (Duret, 2007) (Orée, 2013). The first challenge is the efficient use of materials, energy, and information by firms embedded in the IS network(Ramsheva et al., 2019), because likeany other business or industrial network,firmsface competitionin the market.By convention, IS is understood as the technical and business strategy that relies on inter-firm synergies to minimize cost and improve environmental performance; the IS network, industrial ecosystem, or eco-industrial network refers to the group of firms or actors actually or potentially involved in industrial symbiosis (Chertow, 2007).Thus, the inefficient use of resources can endanger a firm's profitability, which can be enough to interrupt the symbiotic flows, or lead to a withdrawal from the network (Chopra, Khanna, 2014). The second challenge entailsa lack of resilience to external perturbationssuch as natural disasters(Ruth & Davidsdottir, 2009).

Wechose the Altamira by-product synergies case study because it provides a clear arena for territorial by-product valorization in the petrochemical industrial sector, and offers the opportunity to shed light on the influence that efficiency and resilience have on the viability process of IS value chains. The data availability and access to synergic exchanges between actors was were also determinant in our choice of Altamira,which is located in the northwest state of Tamaulipas in one of the largest and most important industrial ports in Mexico. Altamira's petrochemical corridor leads the region's economy and boostsits collective industrial efficiency using the leadership of the local business association.

Theresearch questions addressed in this study are:Is there any benefit/impact in assessing resilience and efficiency in order to achieveIS viability? If so, how can we better assess them in the IS network? The assumptionsassociated with the research question are: 1) understanding of resilience provides improved insights into the viability of the IS network, 2) both efficiency and resilienceassessments could be improved within aterritorial systemic approachin order to better understand the contextual socioeconomic and environmental drivers influencing the IS network.Therefore, we proposeadding resilience as an additionalmeasure to improve IS environmental and socioeconomic viability.

In this paper we provide insights to answer the research questions by applying a case study methodology composed of two methods. The first method studies the material and energy flows depicted in an IS synergies diagram, and the second assesses the influence of efficiency and resilience in IS value chain viability/the viability of IS value chains(Huppes & Ishikawa, 2005)(Boiral, 2005). We observethe influence of efficiency and resilience in IS viability in the second method, which combines material/energy flows analysis (MEFA), economic analysis (EA), and resilience impact (RI) (Diemer & Morales, 2016; E. M. Morales et al., 2019).The findings of the case studyconfirm what is stated in the literature:IS viability improves when the resilience challenge is addressed in addition to the efficiency performance. This study develops specific recommendations to improve IS viability through the application of 1) resilience-reinforcing strategies in firms whoseresilience is compromised and 2) efficiency-reinforcing strategies in firms that obtain marginal benefits from the symbiosis, in an attempt to reduce the withdrawal risk of these firms from the network.

In Section 2, a literature review is devoted to the systemic approach and concept of IS value chains, resilience,and efficiency.In Section 3,we present the methodologyused to assessefficiency and resilienceinIS viability, which includes not only the biophysical material/energy accounting presented in the IS synergies diagram, but also disaggregates the by-product flow,by firm. A descriptive section of the Altamira case study is included in Section 3. In Section 4,we describe the outcomes of the steam, wastewater, waste oil, paper, plastic, sludge, and CO_2 flow exchanges through the IS synergiesdiagram. Efficiency and resilience in IS are assessed and applied to the Altamiracase study to describe their influence in the viability of various value chains. In Section 5,we present adiscussion about the proposed mechanism to calculate viability of IS value chains, addressing the producer and consumer layers. We agree on the influence of resilience in theimprovement of IS value chain viability (Fraccascia, Giannoccaro, & Albino, 2017). In Section 6, we discuss how to improve IS viability by addressing the resilience challenge rather than mere efficiency performance. We discuss the implications of outcomes that show IS viability increase through the application of resilience-reinforcing strategies in the firms where resilience is compromised and efficiency-reinforcing strategies where firms obtain marginal benefits from the Altamira symbiosis networks.Conclusions and recommendations about how to reduce the withdrawal risk of existing firms from the Altamira IS network are offeredin Section 7.

INDUSTRIAL SYMBIOSIS: A LITERATURE REVIEW

In the scientific literature, industrial symbiosis (IS) is characterized by using residues of some supply chain processes as inputs of other supply chains (T. M. Choi et al., 2020), showing value chain interconnections with the three previously described CE bio-based goals. In this study, IS is considered a low-tech innovation and collective business strategy to minimize cost and improve environmental performance. Marian Chertow defines IS as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by-products. IS identifies collaboration and geographic economy as key drivers for the emergence of synergistic possibilities"(Chertow, 2007). While initial studies on IS focused on waste and by-product synergies, later studies have broadened this to encompass other ways to use resources more efficiently, including, for example, the sharing of infrastructure and equipment (Lombardi et al., 2012). Later studies have also focused on the complexity of business models and systemic strategies applied to IS (Short et al., 2014), where the strategies were mainly based on cost reduction and the improvement of environmental performance that relies on inter-firm synergies known in the scientific literature as extended loop strategies (Blomsma, 2018). IS has turned out to be the ideal arena in which to studyviable value chains (VVC) through a territorial approach, but only a few studies have analyzed supply chain viability through integrated methodologies. In this study, the authors/we define IS as a key approach in which business and industry actors seek to achieve VVC, simultaneously ensuring efficiency and resilience improvement, as in the energycase study published by Usón et al., (2012)where environmental and economic assessments are simultaneously computed through the exergy costs of all IS. However, among previous studies regarding IS viability in terms of resilience or efficiency, none of them has addressed both aspects simultaneously, see (Fraccascia, Giannoccaro, & Albino, 2017) and (Yazan, Romano, & Albino, 2016).

The theoretical framework proposed for IS value chains, through a systemic approach in this study,applies insights from supply chain management and industrial ecology (Diemer & Labrune, 2004; Diemer & Morales, 2016; E. M. Morales, Diemer, Cervantes, & Carrillo-González, 2019). Toanswer the research questions of this study,we define networking indicators to calculate the diversity of firms and the redundancyof wastes,along with a cost-impact analysis to calculatethe efficiency of the synergy exchange efficiency of each firm participating in the IS.The IS supply chain structure influences the overall viability of the IS through the efficiency and resilienceof by-product synergic exchanges. The match between by-product supply and demand in IS cannot be easily controlled, since wastes are not produced upon demand but rather emerge as secondary outputs of main production activities (Yazan et al., 2016). Firms depend on each others' waste -if they increase production, the by-product demand is expected to rise, which is translated intomore wastedemand, but if firms try to maximize efficiency at the firm level, the amount of waste produced tends to decreaseinvesting on eco-efficiency technological innovations,which poses a risk for the by-product supply in the IS supply chain. For example, a firm that depends on another firm's wastewater wants to increase individual throughput by maximizing wastewater inflows, while the wastewater supplier wants to minimize it. This is a paradoxsince the wastewater reduction that seems to be an efficiency advantage, ends up having a negative impact on IS resilience (Costa & Ferrão, 2010; Hertwich, 2005).

The literature supports the notion that in IS value chains viability is necessary to enhance resilience(Fraccascia et al., 2020)(Dron, 2013; Fraccascia, Giannoccaro, & Albino, 2017)(Chizaryfard et al., 2020). For instance, the impact of a firm's viability in the IS supply chain has been recognized in the firm's diversity and product ubiquity, boosting resilience in the IS network.The scientific literature also shows that viability in IS boosts collective efficiency, as stated by (Mirata, 2004) (Zhu, Lowe, Wei, & Barnes, 2007). For instance, the viability of the IS pathway to be maintained over time engages an efficient selection of optimal processes and functionalities in the industrial network (M. E. Morales & Diemer, 2019). However, the scientific literature does not answer the question about the influence that efficiency and resilience have or don't have in IS value chain viability. Weargue that efficiency and resilience have a positive influence in IS value chain viability. Viability is not achievable by individual attempts to changea firm's business model, but rather it must involve a systemic change throughout firms, industry value chains, and underpinning societal values, norms, and behaviors.

We present IS value chain performance in amodular way in Figure 1, identifying the adaptive or reactive behaviors of value chains across time in the face of stressorssuch as fluctuations in demand, natural disasters, and global pandemics.

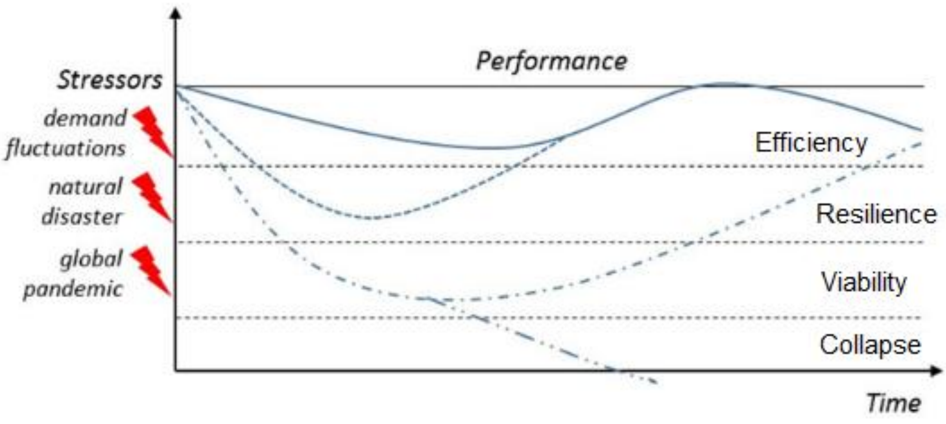


Figure 1. The evolution of value chain performance in the face of extraordinary events
Source: Authors, modified from the work published by (Ivanov, 2020)

This study intends to fill the gap in the IE and supply chain management literature concerning the integration of resilience to the viability or sustainability analysis of IS value chains. We calculate the efficiencyof IS value chains through a cost-impact analysis of synergy exchanges by/of firms participating in the IS.The cost-impact analysis includes the cost savings due to IS implementation, referring to the reduction of waste disposal costs and input purchasing costs. ConcerningIS value chain resilience, we define network indicators of firm diversity and waste redundancy. Networking indicators are based on the impact analysis of events triggered by thewithdrawal of a firm. The supporting information included in Annex1 provides details about the firm resilience index in the case of total disruptions, when IS members decide to exit by-product synergic exchanges.

UNDERSTANDING INDUSTRIAL SYMBIOSIS VALUE CHAIN VIABILITY

One of the main problems that supply chains face today is that, in the pursuit of flow efficiency, they tend to disregard the system's resilience(McCusker, 2018). We argue that IS value chain viability entails both efficiency and resilience of the industrial ecosystem (M. E. Morales & Diemer, 2019). The supply chain analysis of the industrial network is not enough to explain local system dynamics (Nielsen, 2007). Therefore, the present study contributes to breaking down Ivanov & Dolgui, (2020)'s concept of an intertwined supply network and narrowing its scope into local interconnected supply chains aiming to secure the provision of goods and services to society. However, in the context of this study, the scope of intertwined supply networks needs to be limited within the functionality boundaries of the IS life cycle. As evidenced in the literature, current supply chain analysis is not able to integrate resilience and efficiency together(Neves et al., 2019, 2020) through an interconnected network (Boons et al., 2011). Therefore, the value chain concept is used to integrate resilience (Fraccascia et al., 2020) and efficiency activities in supply chains (Abreu & Ceglia, 2018; Domenech et al., 2019), using a functionality approach within territorial boundaries.

Viability is understood as the system's ability to withstand a disruption or series of disruptions while at the same time securing the provision of society and markets in a changing environment (Holling, 1973; Ivanov, 2020). VVC is a dynamically adaptable network able to react agilely to positive changes, be resilient enough to absorb negative events and recover after disruptions, and survive long-term disruptions by adjusting capacity utilization and allocation to demands in response to internal and external changes. Systems theory,when applied to value chains, has many strengths compared to other theoretical frameworks,because it can integrate different supply chainsolutions through a systemic understanding at multiple scales and levels. Recent studies on systems dynamics(Fraccascia & Yazan, 2018; Nasir et al., 2017) support our claim on the complementarity of efficiency and resilience, based on two arguments: 1) IS requires resiliencein order to choose alternative paths to pursue its goal in case of crisis, 2) IS requires economy of scale to process larger amounts of energy, thus reducing overhead. VVC encompasses the supply chain structures and systemic processes that reinforce and balance loops over time. The example of the synergic exchanges of by-products in IS clearly shows the systemic perspectives that stakeholders should integrate into theirassessment methodsin order to improve the management of essential value chains for society, while stressing resilience and efficiency responsiveness.

UNDERSTANDING EFFICIENCY IN INDUSTRIAL SYMBIOSIS

Efficiency stressescost-effectiveness and recognizes the generation of more value with less impact (WBCSD, 2006),(Verfaille & Bidwell, 2000), comparing environmental benefits with the engaged costs of investments(Huppes & Ishikawa, 2005).In this paper, we understand efficiency as a firm's average economic gains coming from production and consumption performance improvements, expressed by the relationship between product and by-product costs and turnover, measured in monetary units (USD). As such, efficiency assesses the performance of an industry by referring to the ability of a firm to produce the maximum turnover for a given set of products and by-products. The stochastic frontier concept(Valderrama, Neme, & Ríos, 2015)assumes that, for a combination of inputs, the maximum production achievable by an industry is delimited by a parametric function of known inputs with unknown parameters and a measure of error. The shorter the distance from the current product to the stochastic or "best practice" frontier, the greater the technical efficiency of the industry. For example, in Mexico technical efficiency is given through a coefficient of the fossil fuel derivate industry(Valderrama, Neme, & Ríos, 2015).

Eco-efficiency investments state that after some optimal level of capacity utilization, the production function will result in diminishing marginal returns. For example, we when the costs invested in technology are higher than the expected benefits, firms start to lose interest in cooperation and synergies became more vulnerable, as shown by Boiral, (2005),whereas[?] we acknowledge smaller increases in eco-efficiency infrastructureinvestments output. The scientific literature on efficiencyissues is wellcovered in the hard sciences, mostly in the engineering fields related toindustry-specific sectors,but it is barely analyzed/touched upon in economics. The development of the firm efficiency concept embedded in the ecosystems approach seems to be crucial to having a systemic understanding of IScollective efficiency(Vanalle, Moreira, & Lucato, 2014) (World Business Council for Sustainable Development, 2006) (Pearce, 2008).

UNDERSTANDING RESILIENCE IN INDUSTRIAL SYMBIOSIS

Resilience was introduced into the ecological literature byHolling (1973), who stated that "resilience determines the persistency of relationships within a system and is a measure of the ability of these systems to absorb changes and still persist". In this paper,resilience is used through its dynamic definitionas "the capability of a system to absorb disruptions and reorganize them while keeping essentially the same structure, function, drivers and flows" (Holling, 1996). In IS, resilience depends on thestructural diversity and redundancyof products and by-products, producers, and consumers. We define IS waste diversity as the number of by-products exchanged between firms and ISwaste production diversity as the sum of by-products produced by each firm. Redundancy is the number of firms that perform the same function, thuswhen applied to IS, redundancy refers to the availability of by-productswithin the system. For example, if a firm without a substitute for the function it supplies is removed from the value chain, the consequences for the system may be more critical than the removal of any other firm with an existing alternative function for the system (Walker, 1992). Resilience has been approached in the scientific literature from different angles, such as risk management (Dauphiné, Provitolo, & Colin, 2007), climate change (Bériot, 2013), urban resilience (Laganier, 2013), andIS analysis (Dron, 2013).

We design the methodology to assess resilience based on the analysis of firm withdrawal, as shown in previous studies such as thosepublished byFraccascia, Albino, et al., (2017), and Schiller et al., (2014). However, the novelty here is that, in addition to diversity and redundancy, resilience stands out as a complex process in the accomplishment of IS value chain viability where IS efficiency also plays a role.A circular supply chain where the wastes are used as inputs (by-products) for other production processes does not necessarily imply the existence of an optimal efficiency process, therefore unexpected outcomes on collective efficiency and resilience could occur when turning value chains into circular IS.

II. METHODOLOGY

The review of extant literature recognizes efficiency and resilience as two keydrivers to assessIS value chain viability using a systemic model over time (t) and space (s). Efficiency is calculated in this study in economic terms, by comparing how much extra money a single firm would spend if it existed outside IS.Resilience is calculatedin this study through inter-firm diversity and waste ubiquity, consisting of the impact analysis of hypothetical firm withdrawal from the IS analysis.We calculatediversity and redundancy through a resilience index, getting data from three categories: 1) firms that produce waste, 2) wastes exchanged and, 3) firms that use the wastes as inputs.

We define the efficiency and resilience of value chains in industrial symbiosis as part of a tandem composed of consumption (C) and production (P). The resilience of consumption (R_C) takes account ofthe diversity and availability of a firm's by-products,which are consumed by others. Theresilience of production (R_P) encompasses the firm's produced by-product diversity andits availability, leading to the calculation of the resilience of the production index. The by-product consumption structure in the index determines the resilience of consumption on itself. The integration of resilience to efficiency indicators gives us a proxy of what we call the IS"viability of value chains (VVC)".

Equation 1. Viability of value chains in industrial symbiosis

$$VVC = \overbrace{(e_C)}^{\text{Efficiency index}} + \overbrace{(R_C + R_P)}^{\text{Resilience index}}$$

We estimate efficiency based on the consumption efficiency calculated through thecost saving resulting from the inclusion of by-products as inputs in the production process (e^C).Consumption efficiency (e^C)assesses the value chain's economic efficiency in industrial symbiosis.Resilience is calculated in this study through the waste production matrix (P matrix) and the waste consumption matrix (C matrix), and the diversity indices, and the by-product redundancy is calculated in the last row and column of Table 2. Production (P) is a *firm's x waste* matrix that replicates the waste's production structure, where the common element P_{ij} denotes the amount of by-product (*j*) produced by firm (*i*) and exchanged within theIS value chains. The resilience of the production index is calculated through the amount of waste produced within the IS, and firm diversity is calculated$D_i^P = \sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}}$as the sum of the ratios between the amount of each by-product produced by (*i*) and the amount of that by-product produced within the IS.We consider resilience inIS as the dynamic system optimizing diversity and redundancy ofthe by-products of both producers and consumers. Redundancy is composed of two elements: 1) redundancy in production, defined as the number of firms that produce the by-product, and 2) redundancy in consumption, defined as the number of firms that use the by-product.

In equations 2.1 and 2.2, the impact index, equation 2.1,is for production (P), and equation 2.2 is for consumption. (C), $\overrightarrow{d_i^P}$ and $\overrightarrow{d_i^C}$ are the vectors for the diversity of firms *i* in waste production and waste consumption, respectively. $R^{P^{-1}}$ and $R^{C^{-1}}$ are the inverse of redundancy for each waste produced and used in every firm, and$\vec{\alpha}$ is the vector which has all elements equal to one, introduced to obtain a scale value (Fraccascia et al, 2017).The resilience index is obtained by subtracting the production impact index (ι_i^P) and the consumption impact index (ι_i^C) for the firm.This equation takes into account the importance of the redundancy and diversity of wastes exchanged.

Equation 2. Impact index for resilience

$$(1) \qquad \iota_i^P = \frac{1}{D_{IS}} * \left[\left(\overrightarrow{d_i^P} * R^{P^{-1}}\right) * \vec{\alpha}\right]$$

$$(2) \qquad \iota_i^C = \frac{1}{D_{IS}} * \left[\left(\overrightarrow{d_i^C} * R^{C^{-1}}\right) * \vec{\alpha}\right]$$

$$(3) \qquad \boldsymbol{\rho_i} = 1 - (\iota_i^P + \iota_i^C)$$

The material and energy flows depicted in the IS value chain synergies diagramdisplays the exchanges in the IS of 9 firms in the Altamira IS, where we recognize three value chains:A, B, and C.The data used in this paper comes from primary and secondary sources. Our primary sources consist of a set of interviews, conducted between December 2016 and March 2017, with corporate managers, intermediators, local policy makers, expert analysts, and board members involved and committed directly or indirectly in the local petrochemical industry in Altamira. The main rationale for choosing these actors was their degree of involvement in IS. Typically, each organization had one designated person in the role of IS network manager and expert. The secondary sources include academic literature reviews, institutional reports, strategic plans, and official local government reports published by the World Business Council of Sustainable Development-Gulf of Mexico (WBCSD-GM) and the Business Association of South Tamaulipas A.C. (AISTAC),dedicated to the by-product synergy project in the Altamira petrochemical corridor.

CASE STUDY DESCRIPTION

Altamira IS takes place in the petrochemical corridor composed of the industrial park, the port, and the Industrial Association of Southern Tamaulipas (AISTAC). Altamira Industrial Park has more than 40 firms with international links to more than 55 countries.It is themost important industrial hub in the state of Tamaulipas and consists of large-scale production companies and long-term investment firms. The

Altamira Industrial Park also contains around 20 large private firms (BASF Mexicana, Biofilm, Flex America, Absormex, Dypack, la Esperanza, Fletes Marroquin, MASISA, Iberdrola, Kaltex Fibers, Mexichem, Polioles, Posco Mexico, Sabic Innovative Plastics Mexico). Altamira Industrial Port facilitates transport connectivityamong the Tamaulipas state in Mexico and the US market, and has the additional advantage of an industrial port that opens up access to the European marketas well as to the main ports on all five continents.

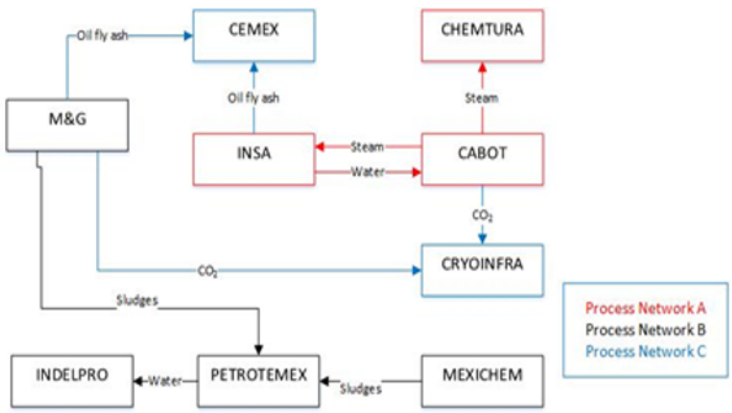
In Altamira's petrochemical corridor,we found out that by-products play a secondaryrole in the viability of IS value chains because by-products are not used in main production activities, but rather in ancillary activities such as cleaning, maintenance, and energy supply.Indeed, we recognize the relevance of a systemic approach in the understanding of eco-efficiency and resilience because, according to Chertow (2007), Morales et al. (2019), and Onita et al. (2006),assessing the viability of IS using a unilateral and oversimplified analysis grid does not provide an optimal understanding of environmental and socioeconomic interrelations. We integrate the resilience dimension into the environmental and economic considerations of our methodology in pursuit of an improvement in IS value chain viability, as shown in previous studies such asArnsperger & Bourg, (2016).

OUTCOMES

This section presentstwo outcomes:1) the IS synergies diagram and 2) the IS value chain viability index,calculated through the efficiency indicator and resilience index in the face of a member of the network's withdrawalfrom the Altamira IS network[?].

ALTAMIRA INDUSTRIAL SYMBIOSIS SYNERGIES DIAGRAM

The Altamira IS network,located in Altamira, Mexico, is described in Figure 2. It hasninelarge corporations—eight multinational firms in the petrochemical sector and onecement firm. To simplify the analysis of the synergic exchanges between these nine actors, three different IS value chains (A, B and C) have been identified.



FIRM	FINAL PRODUCT
INSA	Synthetic rubber resins
CABOT	Black carbon
INDELPRO	Propylene
Chemtura	Plastic additives and lubricants
PETROTEMEX	Purified terephthalate
CRYOINFRA	Industrial gases
M&G Chemical	Poly-ethylene-terephthalate (PET)
Mexichem	Clorox vinyl (PVC)
CEMEX	Concrete and building materials

Figure 2. Chart of Altamira IS synergic exchanges

Value chain A, in red,describes the exchangesamong three firms (f): INSA, CABOT and Chemtura. INSA produces f_1^1 =140,000 tons/year of synthetic rubber resins and provides the wastewater for the symbiotic network $w_1^1 = 950{,}000\frac{m^3}{year}$. CABOT produces$f_2^1$ =140,000 tons/year of black carbon in different forms and receives the wastewater from INSA to be used in the production process. CABOT produces steam as waste,$w_2^1 = 216{,}000\, tons/year$are delivered to INSA and $w_3^1 = 43{,}200\, tons/year$to Chemtura.
Value chain B,in black,outlines the sludge and wastewater exchanges between four different firms: INDELPRO, M&G Chemicals, PETROTEMEX, and Mexichem. PETROTEMEX produces f_1^2 =1,000,000 tons/year of purified terephthalate and provides $w_1^2 = 450{,}000\, m^3/year$ of wastewaterto INDELPRO. M&G Chemicals producesf_2^2 =450,000 tons/year of poly-ethylene-terephthalate (PET). Mexichem producesf_2^2 =140,000 tons/year of clorox vinyl (PVC). M&G Chemicals and Mexichem provide the waste sludge consumed by PETROTEMEX, $w_2^2 = 40\, tons/year$of sludge waste produced by M&G Chemicals and $w_3^2 = 30\, tons/year$ by Mexichem. If handled properly, the sludge can be a

valuable resource for renewable energy production, because energy recovered from sludge incinerationcan be turned into thermal and electrical energy. The main part of the sludge's dry matter content consists of non-toxic organic compounds, so energy recovery is an important alternative source forheat generation. The amount of energy that can be obtained depends on the water content, incineration performance, mechanical dewatering, and drying of sludge (Vatachi, 2016).

Value chain C, in blue,describes theoil fly ash and CO_2 exchange, involving CRYONFRA and CEMEX. M&G Chemicals and CABOT provide $w_1^3 = 200{,}000\ tons/year$ and $w_2^3 = 115{,}000\ tons/year$, respectively, of CO_2 directly used by CRYOINFRA in its production process. M&G Chemicals and INSA provide $w_1^1 = 2\ tons/year$and $w_1^1 = 2\ tons/year$, of oil fly ash, respectively, used by CEMEX in its concrete production process, i.e.,f_1^3 =20,000,000 tons/year, made by INSA. The amount of CO2 received as a by-product by CRYOINFRA is known, but we do not know the production capacity of the company;this information was not revealed because of their secrecy and confidentiality policy.

The main by-product users in the Altamira IS network are CABOT, INDELPRO, CRYOINFRA and INSA.Together they consume 98% of the total by-product material inflows, representing more than 1.9 million tons/year. The highest flow in volume is wastewater; CABOT and INDELPRO are first and second in terms of consumption levels. For material production, the four firms that produce 100% of the by-products at Altamira are INSA, PETROTEMEX, CABOT and M&G Chemicals.Consumer and producer firms are not the same; the main by-product consumers INDELPRO and CRYOINFRA are not on the IS material consumption list. Chemtura, CEMEX and MEXICHEM do not take advantage of the IS network, even if CEMEX has significant fly-ash consumption potential, but M&G Chemical's and INSA's production capacity (2 tons/year each) is minimal in comparison with CEMEX's needs. CABOT, INSA and INDELPRO obtain the main benefit of material exchanges in the ISvalue chain.The by-product inputs used as energy consumption in theIS value chains are represented only by INSA and Chemtura, which use steam and sludge as energy sources. CABOT is the only producer of steam, supplying 259,200 tons in the Altamira IS network. Even when the flows reach more than 132,359 giga calories/year, only two companies consume residual energy: INSA and Chemtura, keeping the energy difference between production and consumption in a range of 7% (Lule & Cervantes, 2010).

VALUE CHAIN EFFICIENCY IMPACT IN INDUSTRIAL SYMBIOSIS VIABILITY

In the Altamira case study, relevant insights on the efficiency in the IS value chains have been integratedinto the viability analysis. Symbiosis in the IS petrochemical corridor entails the reuse of by-products from chemistry, manufacturing, fossil fuels, and waste treatment that are absorbed and reintegrated into the system loops. The present study argues/contends/highlightsthat the industrial ecology and supply chain management literature share many similarities. This paper aims to shed light on the relationship between value chain efficiency and viable industrial symbiosis able to react adaptively to positive changes, absorb negative disturbances, and survive during shocks. However, the increase of waste availability and its use as by-productscould become a problem because these are not traditional commoditiesand because their production depends on the main production's capacity.Firms in the Altamira IS network encourage waste production strategies because they are no longerrecognized as waste;however, if a by-product'smarket price is attractive enough, an increase in the demand could boost main production up to a point wherea by-product becomesa commodity, changing the initial allocation of the IS variables and endangering the viability ofsynergies.In Table 1,we show that INSAgets the largest economic benefits, $/year, followed by CABOT at US$323,000; M&G Chemicals, and Mexichem achieve almost no monetary savings from the synergies. The IS efficiency gains are calculated using the aggregated relative efficiency in production per company (s), the total substitution cost (US$1,105,172.50) comes out from theby-product savings.

Firm	By-product used	Quantity used	Unit	Unit price (USD)	By-product savings (USD)	Percentage of substitution costs	Efficiency gain disaggregated per firm	Efficiency indicator
CABOT	Wastewater	950,000	m^3/year	$0.34	$323,000.00	29%	11%	0.79
INSA	Natural gas	53,080	MMBtu/year	$8.95	$475,066.90	43%	15%	0.83
INDELPRO	Wastewater	450,000	m^3/year	$0.34	$153,000.00	14%	5%	0.75
CRYOINFRA	CO_2	315,000	ton/year	$0.17	$53,550.00	5%	2%	0.73
Chemtura	Natural gas	10,620	MMBtu/year	$8.95	$95,047.84	9%	3%	0.74
CEMEX	Oil fly ash	4	ton/year	$1,204.43	$4,817.72	0%	0%	0.72
PETROTEMEX	Natural gas	77	MMBtu/year	$8.95	$690.05	0%	0%	0.72
TOTAL					**$1,105,172.50**	100%		

Table 1. Altamira IS economic savings resulting from by-product use

Source: Authors

Notes:
1. Units in US dollars at the exchange rate to pay obligations entered into in U.S. dollars payable to México on September24th, 2021, (Bank of Mexico, 2021).
2. Water costsare determined by the hydrological basin where Altamira is situated (CONAGUA, 2016).

The technical efficiency in consumption of Mexico's chemical industry is 0.717 (Valderrama, Neme, & Ríos, 2015), and the total estimated IS efficiency gain from synergic exchanges in 2016 (E. M. Morales et al., 2019) is calculated by the AISTAC at 4% among all nine involved/participating firms, with an average savings of 11.11% of the $1,105,172.50 USD total economic savings from the substitution of inputs in the production process. INSA, with a 43% share of these total efficiency gains,has obtained a 15% increase in efficiency, which drives the efficiency indicator to 0.82 when disaggregated by firm. When calculating the new efficiency values for each firm, the gain in productivity added to the technical efficiency of the chemical industry in Mexico suggests new values for INSA, CABOT, INDELPRO and Chemtura of 0.83, 0.79, 0.75 and 0.74, respectively. INSA is the firm which gains the biggest efficiency benefits from the IS with 15%, followed by CABOT with 11%. Overall, the Altamira IS network has a high degree of efficiency concentration, providing significant benefits to only two firms. This can partially be explained by the multiple interconnections developed in the IS by the previous firms, and by the fact that they are IS founding members, with a long history of cooperation, formal and informal communication, social connections, reciprocity, and trust.

VALUE CHAIN RESILIENCE IMPACT IN INDUSTRIAL SYMBIOSIS VIABILITY

The three value chains in the Altamira IS involveninefirms exchangingfive different types of waste. The way in which waste production firms influencethe resilience of value chains in the IS is observed in Table 2. In the last row of Table 2, we observe that waste production redundancy is 1 for steam and 2 for all other wastes, indicating that there is only one producer of residual steam in the industrial network, while there are at least two suppliers for all the other by-products.

Waste production in Altamira, by firm	Steam (t)	Wastewater (m^3)	Oil fly ash (t)	Sludge (t)	CO_2 (Kton)	**Firm diversity index**
CABOT	259,200	0	0	0	115	**1.3651**
M&G Chemicals	0	0	2	40	200	**2.0714**
INSA	0	950,000	2	0	0	**1.1786**
PETROTEMEX	0	450,000	0	0	0	**0.3214**
MEXICHEM	0	0	0	30	0	**0.4286**
CRYOINFRA	0	0	0	0	0	**0.0000**
CEMEX	0	0	0	0	0	**0.0000**
CHEMTURA	0	0	0	0	0	**0.0000**
INDELPRO	0	0	0	0	0	**0.0000**
Waste redundancy index (U^P)	**1**	**2**	**2**	**2**	**2**	

Table 2. Waste production in Altamira IS network, by firm

Source: Authors

In Table 3, we observe the network analysis of waste consumption firms in the Altamira IS network. Steam has replaced the consumption of natural gas for INSA and Chemtura. Wastewater consumed by the firms in the IS network have a redundancy of two, and other wastes like oil fly ash, sludge, and carbon dioxide show a redundancy of one, which means that in the IS network there is only one firm consuming the existing by-product. Therefore, if this consuming entity withdrew from the IS network, the symbiotic exchange would be lost. In the Altamira IS network, firms produce on average two different wastes and use only one. The firm diversity index ranges from 0 to 2.0714 for production and from 0 to 1 for consumption. On average, 1.8 firms produce each waste material and every waste material is produced by 2 firms, with the exception of steam, which is only produced by CABOT;1.4 firms use every type of waste.

Waste consumption in Altamira, by firm	**Steam (t)**	**Wastewater (m^3)**	**Waste oil (t)**	**Sludge (t)**	**CO_2 (Kton)**	**Firm diversity index**
CABOT	0	950,000	0	0	0	**0.6786**
M&G Chemicals	0	0	0	0	0	**0.0000**
INSA	216,000	0	0	0	0	**0.8333**
PETROTEMEX	0	0	0	70	0	**1.0000**
MEXICHEM	0	0	0	0	0	**0.0000**
CRYOINFRA	0	0	0	0	315	**1.0000**
CEMEX	0	0	4	0	0	**1.0000**
CHEMTURA	43,200	0	0	0	0	**0.1667**
INDELPRO	0	450,000	0	0	0	**0.3214**
Waste redundancy index (U^c)	**2**	**2**	**1**	**1**	**1**	

Table 3. Waste consumption in Altamira, by firm

Source: Authors

Theresilience indexpresented in Table 4 is calculated using equation 2, displayed in the methodology section. The resilience index summarizesthe (1) productionand (2) consumption equations(presented in Tables2 and 3), which testthe effects of a disruptive event consisting ofa firm'swithdrawal. For example,the removal of CABOT would be more critical than the withdrawal of M&G Chemicals. If M&G Chemicals stopped sludge exchange, $CO_{2,}$ and oil fly ash exchange would continue, because

Mexichem, INSA, and CABOT would ensure the supply. Thisdemonstrates that the Altamira IS network is more resilient to a disruptive event happening at M&G Chemicals than to onehappening at CABOT, the only steam producer, which has a low level of redundancy waste, becausethe "steam" function would be lost if CABOT left the IS network.

Table 4. Resilience (ρ_i is highlighted in bold), impact measures in Altamira

	Resilience index		
Firm	ι_i^P	ι_i^C	ρ_i
CABOT	0.136508	0.067857	**0.7956**
M&G Chemicals	0.414286	0	**0.5857**
INSA	0.117857	0.083333	**0.7988**
PETROTEMEX	0.032143	0.2	**0.7679**
MEXICHEM	0.042857	0	**0.9571**
CRYOINFRA	0	0.2	**0.8**
CEMEX	0	0.2	**0.8**
CHEMTURA	0	0.016667	**0.9833**
INDELPRO	0	0.032143	**0.9679**

Source: Authors, data used to create Table 4 can be found in the Supporting Information *(SI)*section

III. DISCUSSION

This study aims to integrateresilience intoIS value chain viability assessment. The study aims tomove IS analysis away from the risky logic of excessive focus on efficiency through acomprehensive approach.We find evidence based on the data collected from firms inthe Altamira IS network in 2017 suggesting that when including the resilience and efficiency assessments, we reach a better and systemic understanding of IS value chain viability. Figure 3illustrates the efficiency and resilience indices for the Altamira ISnetwork in 2016. In Figure 3, we observeefficiency (blue line) determiningthe system's ability to maximize economic throughput, thanks to the cost savings of using wastes as productive input, and resilience (orange line) determiningthe system's ability to allow for divergent processes by maintaining a degree of freedom that will ensure the IS network'sfunctionality.

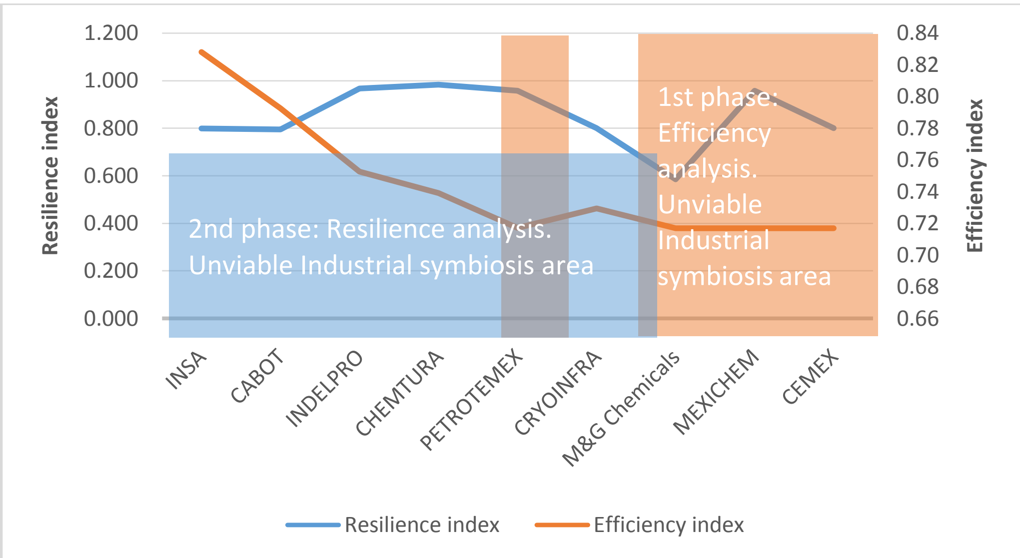


***Figure 3.* Efficiency and resilience indices from the 2016 Altamira IS case study**

As observed in Figure 3, the horizontal axis represents all the firms in the Altamira IS network.The first screening phase identifies firms that are not gaining efficiency from industrial symbiosis and can be thus considered unviable IS actors: M&G Chemicals, MEXICHEM, CEMEX and PETROTEMEX. In the second phase, we analyze the resilience of INSA, CABOT, INDELPRO, CHEMTURA and CRYOINFRA, identifying INDELPRO and CHEMTURA as the firms with the best performance; therefore, we argue that these two firms positively influence the Altamira IS network's value chain viability. When analyzing the resilience of IS value chains, we find that IS value chain B is the only onein which all participating firms areboth efficient and resilient. Thus,we argue thatvalue chain B is the anchor in the IS network, entailing a comprehensive process of resilience and efficiency that are working in conjunction to improve/achieve viability.

Our findings suggest that by adding a resilience assessment to the economic efficiency indicators, we were able to achieve asystemic understanding of theviability of IS value chains. The integration of resilience into the conceptual efficiency approachleads toa transition fromamainstream individualistic firm approach to a systemic approach of IS interrelations, already suggested byMeneghetti & Nardin, (2012). Thesystems approachcannot keep the same accountancy tools and measures of thefirm approach;theIS value chains viability must beanalyzed at a meso-level scalethrough methodsthat are able to handle the complexity of inter-firm symbiotic relationships(T. Y. Choi et al., 2001).

The proposed strategy to promote value chain viability entails technology and infrastructure investments to encourage the firms participating in value chains A and C to move into a position where both efficiency and resilience criteria will be fulfilled, triggering the viability of the three existing value chains in the Altamira IS network.Strategies to improve IS value chain viability should not disregard the fact that there is an efficiency threshold in the productive function of synergy exchanges, embedded by the full installed productive capacity of the main production process.If the by-product production targetsa higher by-product production level, this has to beanticipatedwell in advance in order tomake the necessary infrastructure investments.

IV. CONCLUSION

Industrial symbiosis (IS) is recognized as one of the most promising strategies to pursue and achieve viability in productive value chains. The modular integration of resilience and economic efficiency assessments into the understanding of IS systemsaims to encourage the viability objectives of IS value chains through synergic exchanges. The scientific literature emphasizes the idea that efficiency should be accompanied by resilience, restoring structural balance in the IS,in order to achieve systemic value chain viability. In this study, to avoid efficiency oversimplification in the IS, we include resilience network analysis through the diversity of firms producing byproducts in the network and the redundancy of wastes of producers and users in the existing IS supply chains. Outcomes point out that the viability of industrial symbiosis can only be analyzed through the value chains composing the ISvalue chain[?], addressing the producer and consumer exchanges concurrently.

We conclude that,according to the size and length of stressors influencing the IS dynamic, modular strategies should be implemented to anticipate potential scenarios where short-term, long-term, and structural stressors will endanger the viability of the IS network/value chain. The economic efficiency of firms that make up IS value chains allows firms toovercome short-term stressors.The resilience in byproduct synergies of firms participating in an IS value chain allows them to build adaptive changes in IS value chain to overcome long-term stressors such as natural disasters. Finally, the integration of both efficiency and resilience assessments in synergic exchanges ensures the viability of value chains in response to systemic and long-term stressors such as climate change and global pandemics.

The Altamira IS demonstrates a high degree of efficiency and resilience in value chain B, putting the firms CABOT, CHEMTURA and INSAat the core of the ISin term of its viability.The methodology we use in this study presents a modular integration of efficiency and resilience in two consecutive screening phasesof the Altamira ISnetwork to define whether there is an influence of both variables in the viability of the IS value chains.The presented method provides independent outcomes regarding efficiency and our resilience assessment proposes specific and modular recommendations that could facilitate decision makers to define collective strategies to improve ecosystem viability. We recommend the application of these modular assessments to define the current situation of each firm embedded in the IS value chains, facilitating the definition of customized strategies according to the stage of evolution of each firm and its ongoingrole in strengthening the synergic relationships in the industrial ecosystems..

Some relevant questions are evoked in this paper:for instance,what is the desirable efficiency and resilience structure in IS? How can we define the efficiency thresholds in IS? Exploration of these questions may provideinsight to define future research projects.We show as an outcome of this study that value chain viability depends on shared flexibility and a balancebetween resilience and efficiency, leading to further avenues of research to explore the system complexity in IS and its influence on the system's performance (Douai & Montalban, 2012). Other relevant paths for further research entail the integration of other variables in the analysis,for instance, cooperation, competition, governance style, and local/global scale of IS,as well as asensitivity analysis of other kinds of waste utilizationrather than of by-product exchange synergies.This study is not exempt from criticisms related to the research method in terms of robustness and validity, due tothe static aspect of the study. A dynamic approach with historical datain Altamira and otherIS networksmay help to achieve a better understanding of IS value chainviability.

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