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Industrial symbiosis, a model of strong sustainability:

An analysis of two case studies, Tampico and Dunkirk

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par

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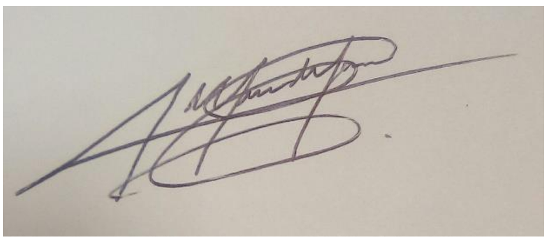

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FOREWORD

This thesis is the outcome of a research effort that encompasses a set of published papers with the intention to unfold a clear narrative string. It addresses industrial symbiosis as an inter-firm innovative strategy looking forward to achieve strong sustainability in developing and developed countries. One of the benefits of the system's causality understands improvement, and the knowledge management (Mauelshagen et al., 2014) goes beyond the merely analytical-deliberative process integrating technical assessments and social values to produce legitimate policy design and outcomes. Given that IS cannot expect strong sustainability accomplishment if its governance does not place significant effort into managing and supporting this collaborative network, with a complementary commitment in efficiency and resilience, as well as conciliating local and global issues.

Our study aims to provide a territorial and systemic approach able to integrate the complexity of motivations and values sometimes contradictory between stakeholders, seeking to provide a rigorous and coherent framework for public/private policy recommendations. For this purpose, we call on some disciplines like economics geography, industrial ecology and systems analysis.

The thesis structure encompasses:

- An introduction, presenting the context of the study, the state of the art related to industrial symbiosis, the research questions and objectives of the dissertation, the theoretical assumptions we state and the theoretical framework we call to bear the assumptions we previously state. We present the methodology and the relevant outcomes we obtain when giving answer to the research questions analyzed.

- A set of seven scientific papers, published or under revision, inquiring in the theoretical foundations, the literature review on what we build the theoretical assumptions stated, and the methodology process that we draw up to analyze the case studies in France and Mexico.

- Finally, the conclusion highlights the main outcomes of the study and the theoretical and methodological contributions shedding light to the analyzed problematic.

ABSTRACT

Industrial symbiosis (IS) is presented as an inter-firm organizational strategy with the aim of social innovation that targets material and energy flow optimization, but also structural sustainability. In this study, we present systems thinking and geographical proximity as the theoretical framework used to analyze industrial symbiosis through a methodology based on System Dynamics and the underpinning use of Causal Loop Diagrams, aiming to identify the main drivers and hindrances that reinforce or balance the industrial symbiosis's sustainability. The understanding of industrial symbiosis is embedded in a theoretical framework that conceptualizes industry as a complex ecosystem in which qualitative and quantitative approaches can be integrated, if we use a methodology flexible enough to encompass the complexity of the stakeholder's values and motivations in the same analysis. Furthermore, the methodology performs a comparative strength over descriptive statistical forecasting, because it is able to integrate social causal rationality when estimating attractiveness in a region or individual firm's potential. The stakeholders' influence becomes essential to the complex understanding of this institution, because by shaping individual behavior in a social context, industrial symbiosis provides a degree of cooperation in order to overcome social dilemmas for actors like the tension between efficiency/resilience, who cannot be achieved by their own. The proposed narrative encourages us to draw up scenarios, integrating variables from different motivational value in the industrial symbiosis. We use the Altamira and the Dunkirk case studies to explain the role of geographical systems analysis, identifying loops that reinforce or regulate the sustainability of industrial symbiosis, and three drivers: "Efficiency/Resilience dilemma", "Industrial symbiosis governance", and "The role of global recycling networks in the by-product valorization". The social dimension integration in the analysis of a complex system is indeed applied to enhance the understanding of IS dynamics, but a great potential is foreseen for other micro-level social systems like for example urban metabolism dynamics or bio-economy.

Keywords: Industrial symbiosis; Dunkirk; Altamira; complex analysis; system dynamics; social systems

RESUMEE

La symbiose industrielle (SI) est présentée comme une stratégie organisationnelle d'innovation sociale inter-entreprises, visant à optimiser les flux de matières et d'énergie, mais également la durabilité structurelle. Dans cette étude, la pensée systémique et la proximité géographique constituent les deux piliers du cadre théorique de la symbiose industrielle. La dynamique des systèmes et son utilisation des diagrammes de boucles causales, permet d'identifier les variables clés (key drivers) qui renforcent ou régulent les systèmes industriels. L'analyse de la SI s'inscrit dans un corpus théorique qui conceptualise l'industrie en tant qu'écosystème complexe à l'intérieur duquel des approches qualitatives et quantitatives peuvent être intégrées, de manière à englober la complexité du système et les motivations des parties prenantes. Un avantage important de la méthodologie utilisée repose sur sa capacité à intégrer la dimension sociale d'un territoire ou d'un réseau d'entreprises. La structure des interactions causales entre les acteurs de la symbiose joue ici un rôle important, car en façonnant les comportements individuels dans un contexte social, la symbiose industrielle offre un degré de coopération permettant de surmonter les dilemmes sociaux auxquels sont confrontés les parties prenantes. Les scénarios proposés dans cette étude sont ainsi susceptibles de prendre en compte la diversité des motivations des acteurs au sein d'une symbiose industrielle. A partir des études de cas, Altamira (Mexique) et Dunkerque (France), nous avons cherché à identifier les boucles qui renforcent ou régulent la durabilité de la symbiose industrielle. Trois dynamiques ont été mises en avant : « le rapport Efficacité / Résilience », « la gouvernance de la symbiose industrielle » et « le rôle des réseaux de recyclage dans la valorisation des coproduits ». L'intégration de la dimension sociale dans l'analyse des systèmes complexes est préconisée pour améliorer la compréhension de la dynamique de la SI. Ce travail de recherche ouvre de nombreuses perspectives en matière d'analyse des systèmes sociaux, que ce soit l'étude du métabolisme urbain ou la mise en place d'un programme bioéconomique.

Mots clés : Symbiose industrielle, Dunkerque, Altamira, analyse complexe, dynamique des systèmes, systèmes sociaux

ABBREVIATIONS TABLE

AISTAC	Industrial Association of South Tamaulipas A.C.
ABP	Altamira By-Product
ADEME	Environmental and Energy Control French Agency
AGSEO	Analysis and Socioeconomic Management Organization
AGUR	Urban planning and development of Dunkirk city
BPS	By-Product synergie
CAM	City analysis methodology
CAS	Complex Adaptive Systems
CEMEX	Mexican Concrete Company
CEO	Chief Executive Officer
CERDI	Research Centre of Economic Studies and International Development
CEWEP	Confederation of European Waste to Energy Plants
CFE	Mexican Electricity Federal Agency
CICATA	Research Centre of Applied Sciences and Technology
CiViTaS	City, Vitality and Sustainability initiative in Burgos, Spain
CLD	Causal Loop Diagram
CNRS	French National Centre of Scientific Research
CO	Carbone monoxide
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
CONACYT	Mexican National Agency of Science and Technology
CONAGUA	Mexican Water National Agency
COV	Volatile organic compound
DESA	Department of Economic and Social Affaires
EA	Economic Analysis
ECOPAL	Economy & ecology partners in territory actions - Dunkirk

EDF	French Energy Company
EFA	Energy Flow Analysis
EPA	Environmental Protection Agency
EU	European Union
EU28	European Union (BE, BG, CZ, DK,DE, EE, IE, EL, ES, FR, HR, IT, CY, LV, LT, LU, HU, MT, NL, AT, PL, PT, RO, SI, SK, FI, SE, UK)
GHG	Greenhouse gases
GIEI	Industrial Ecology Research Group
GWh	Giga watts hour
ICLEI	International council boosting the local ecological initiatives
IE	Industrial Ecology
IMF	International Monetary Fund
IRD	Development Research Institute
IS	Industrial Symbiosis
ISD	Industrial symbiosis diagrams
ISIE	International Society of Industrial Ecology
ISN	Industrial Symbiosis Network
ISRS	Industrial Symbiosis Research Symbiosis
ITE	Industrial Territorial Ecology
Kcal/kg	Kilocalories/kilograms
Kcal/ton	Kilocalories/tonnes
Kg	kilograms
KWh/kg	Kilowatts. Hour/kilograms
LCA	Life cycle analysis
M3/year	cubic meters/year
MEF	Material Energy Flows
MEFA	Material Energy Flow Analysis
MFA	Material Flow Analysis

MMDS	Mental models dynamic system
MSW	Municipal solid waste
Mt	Megatons
NGO	Non-Governmental Organization
NOx	Nitrogen oxide
OECD	Organization for Economic Co-operation and Development
OR2D	Sustainable Development Partners Association
OSHA	Occupational Safety and Health Administration
PEMEX	Mexican Petroleum
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
REV	Rebuilding Economic Vitality
RIS	Regional Industrial System
SC	Supply chain
SDG	Sustainable Development Goals
SEC	Securities and Exchange Commission
SFD	Stock and Flow Diagrams
SL	Social system
SME	Small and medium enterprise
SNA	Social Network Analysis
SO2	Sulphur dioxide
SUM	Sustainable Urban Mobility
TJ	Tons of Joules
UCA	Université Clermont Auvergne
UK	United Kingdom
ULIN	Université de Lausanne
UN	United Nations
UNEP	United Nations Environmental Program

UNS	Units for steel (metal alloys)
US	United State
USD	United state dollars
WB	World Bank
WBCSD	World Business Council for Sustainable Development
WFD	Waste Framework Director

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SUMMARY

INTRODUCTION

In less than 10 years from 2003 to 2012, global waste generation per capita has increased by more than 87% (Hoornweg & Bhada-Tata, 2012), the world is generating waste faster than any other environmental pollutant including greenhouse gases. Urban cities have taken the main role as the larger solid waste producer in the world[1] (Hoornweg, Bhada-Tata, & Kennedy, 2015), and are home to most industries which are foreseen to double the extractions of non-renewable resources by 2025 and triple by 2050, according to the IRP by the UNEP. The increase in the extraction of non-renewable resources depends on the expected increase in the worldwide purchase power, because by 2100 almost all countries will be defined as high income by the (World Bank, 2019) convention (GNI per capita of $12,056USD or more) under most scenarios. Population became a central issue in the cities, considering that by 2050 more than 68% of world population is projected to live in cities, grown rapidly from 751 million in 1950 to 4.2 billion in 2018 and expecting to attempt 9.7 billion by 2050, according to (UN-DESA, 2018). Asia, despite its relatively lower level of urbanization, is home to 54% of the world's urban population, followed by Europe and Africa with 13% each.

Today, the most urbanized regions include Northern America (with 82% of its population living in urban areas in 2018), Latin America and the Caribbean (81%), Europe (74%) and Oceania (68%). Considering the expected growth in urban population and consumption behaviors in urban areas, we assume cities as the best-organized structure available to humans in the effort to tackle global challenges in a systemic way. Cities should enterprise different strategies to tackle the peak of waste generation, resource extraction and population from different fronts: mitigation (strategies to reduce the slope of the growth curve) and adaptation (strategies to better handle the effects of this growth) in the sought of sustainability. Taking the worldwide population expectancy out of the scope of this study, we took the waste management and the resource extraction rates as the challenges to be addressed by this study. The holistic project aiming to deal with those challenges is the Industrial and Territorial Ecology (Geissdoerfer et al., 2017)(Saavedra et al., 2018), which applied in urban areas is looking forward to replace the end-of-life concept (Tsujimoto et al., 2017), shifting towards reuse and return to the biosphere.

[1] Rural residents generate less waste than their urban counterparts, and with greater land availability, waste disposal is less pressing

Instead of consider waste as an undesirable effect of production process, generating an outcome that lacks utility and economic value, usually translated into pollution, and tackled as a negative environmental externality (Daly, 1991), industrial ecology approaches waste as a circular issue (cradle-to-cradle) (Geissdoerfer et al., 2017). In line with the scholar literature reviewed in (Gregson, Crang, Fuller, & Holmes, 2015) and practitioners literature IE entails waste recovery and revalorization as raw materials, where recycling represents more than 50% of MSW diverted from landfills in Europe by 2020.

In the IE field, recycling has gained purchase as public policy to address the waste problem. It is not hard to see its appeal. The concept appears to decouple economic growth from increasing resource use, as well as promoting waste reduction and minimization. The integration of global recycling streamline as the most widely acceptable public policy tends to be approbatory, uncritical, descriptive and deeply normative, but given its prominence is important to submit recycling to a critical analysis, because we believe that there are good and bad ways of keeping materials and energy circulating. Notwithstanding that, there is not a miracle formula or a waste management prioritizing equation like the Waste Hierarchy[2] proposed by the WFD that works well without taking into account the social and environmental context. The case studies in (Gregson et al., 2015), present some Recycling problems in the UK, giving evidence of how easy the confluence of politically created markets and the material properties of wastes can result in the production of low-value products, confirming that recycling in global networks could became a wrong way to enact circularity in a given territory.

The current challenge is to be critical, when analyzing the available alternatives to enact circularity of materials and energy in a specific territorial configuration. The analysis of the complex social ecosystem draw up a dynamic structure adapted to differing moral values, and

[2] The waste hierarchy (Hultman & Corvellec, 2012) cited in (Gregson et al., 2015) states a preferential ranking which prioritizes ways of managing wastes on the basis of their environmental benefits. At the top of the hierarchy is waste prevention. Below this is recovery for use, followed by recycling in which waste materials are reprocessed into products, materials or substances, which may be for their original, or other purposes. Followed by the byproducts exchange, that could be either "up-cycled" or "down-cycled", where energy recovery (i.e. heat and steam) are less favored than recycling.

not just physical or technical mechanisms, to rekindle value in recalcitrant waste materials. In a way that makes IE able to integrate social complexity, providing adapted tools and methodologies to facilitate the decision making in the public and private sphere, incorporating other strategies, more than global recycling, in the sought of sustainable strategies to turn wastes into resources.

Indeed, we limit the boundaries of this study to the "supply and demand for goods and services", specifically the field of study corresponding to industrial and territorial ecology challenges and objectives. In this study, we consider industrial ecology entailing theoretical foundations embodied in the strong sustainability that makes it different from the circular economy concept, and one of the main theoretical differences is that the former holds the capital substitutability assumption beyond the full material and energy circularity potential. Another practical difference is that circular economy' action arena thinks about individual firms' as the dynamic unit of analysis encompassing eco-conception, eco-efficiency and length of use extension, while the latter is rather interested in inter-firm cooperation. Even when assumed in the IE literature, from the best of our knowledge this is the first time that the scope is clearly delimited leaving individual firms' improvements and competitiveness out of IE's research field.

Since the beginning of the IE conceptualization as scientific discipline, the holistic and systemic outlook feed its relationship with the biosphere, establishing a metaphor with the ecological ecosystems dynamics; considering firms as organisms exchanging material and energy within them and with the environment. In this metaphor, the industry entails a semi-closed ecosystem where material and energy flows should be reincorporated in the system by a circular logic. However, it does not mean that inter-firms actions do not concern individual firms; on the contrary, individual firms must integrate IE in the individual project of each company to allow communication and interdependency as members of the system. Some actions to integrate IE in the firm's project are i.e. the identification of resource flows (input/output) accountancy, the identification of synergies opportunities, as well as the adoption of the systemic understanding.

The main issue addressed by IE in this study is the industrial, commercial and institutional (ICI) waste with more than 50% of MSW in urban areas (Hoornweg & Bhada-Tata, 2012) represents much more than households waste. In addition, many industrial processes have by-products valorization potential, with a relatively easier technological access and quality control, entailing in most cases one of the first drivers with the ability to change the industry structure towards a circular logic tackling the waste management, consumption behavior and scarcity of resources. At current rate, waste generation is expected to triple and exceed 11 million tons per day by 2100, setting waste management as a central issue. Indeed, two options are currently available to deal with this issue, whether to invest on higher rates of waste management efficiency (recycling, decomposition, incineration, etc.), or seeking to reduce waste generation from the source. Therefore, the reduction in waste could be achieved only by two pathways, a consumption behavior shift (barely possible if we take into account the statistical estimations of worldwide purchase power increase) (World Bank, 2019) or the implementation of industrial ecology principles.

Given that, most scenarios estimate marginal or inexistent possibilities to reduce industrial waste through "end of pipe" efficiency and technological innovation, it is a completely risky behavior to rely merely on the current researches on technical efficiency to tackle those challenges. Addressing the global waste and extraction rate and consumption behavior challenge will, more-over, involve widespread application of Industrial Ecology, as well as further advances in material flow accounting, sustainable supply-chain management, product stewardship and life cycle management. Thus, we strongly believe that IE principles, as a disruptive[3] innovation represent a viable alternative to shift the environmental struggle tendency, holding on the ability to transform global society into a one that conserve and makes better use of materials.

In doing this, we are assuming that social innovations in the industry could be triggered by metaphors, which make us think out of the box. In the 90's, two General Motors' employees wrote the seminal paper that gives birth to industrial ecology, Robert Frosch, vice-president of research, and Nicholas Gallopoulos, head of engine research (Frosch & Gallopoulos, 1989). Both underlined the compulsory need to move from a linear economy where resources are

[3] A disruptive event is defined as any event able to affect the feasibility conditions of the IS relationship, altering the current equilibrium state of the IS from a technical, economic, and/or standards point(s) of view (Garner & Keoleian, 1995)

extracted from the ecosystem, exploited by human activities and returned to a degraded ecosystem in the form of waste, depicting the stocks and flows trajectory, recycling used goods and limiting waste (Dannequin, Diemer, Petit, & Vivien, 2000). Although IE introduces a theoretical conceptualization of ecology as an experimental science at an early stage, the methodologies and scopes applied allow us to see that the social understanding of this discipline is desirable for a better understanding of industrial ecosystem dynamics. This is what the French school claims in ITE (Buclet, 2011) then simply Territorial ecology (Buclet, 2015) using a systemic approach to the social dynamics of industry (Ayres & Ayres, 2001), and looking beyond firms' individual actions in the search for eco-efficiency.

While digging in the literature review, we did not find a corresponding set of strategies that correspond with the underpinning definition of IE. For example, according to (Erkman, 2004) the strategies leading this transition explore four directions: waste recovery; energy and materials loop closing, reduction of the dissipative emissions; dematerialization of products and services; and de-carbonization of energy. This set of strategies introduced to accomplish the IE's principles, does not make a difference between the individual strategies that a single firm could endeavor in the frame of internal eco-efficiency of its productive processes, and the IE's principles. Even when positive for the firms, if those strategies are not related to the interaction within stakeholders or between the stakeholders and the environment (social and biophysical), this relationship is out of the scope of the IE discipline. Therefore, after a deep literature review, we propose a set of strategies that match the IE framework and conceptualization.

Table 1. IE encompassing strategies

INDUSTRIAL ECOLOGY		
Project	**Strategies**	**Definition**
Energy and materials loop closing (Synergies)	Dematerialization synergies	When two entities look for the substitution of tangible solutions by intangible solutions, shifting the product-based solution to a fulfilling needs logic (outsourcing, decentralization processes, involving third-party contractors for distribution and maintenance.)
	Decarburization synergies	When two entities relationship substitute the fossil fuel stream by an alternative renewable fuel stream (from waste) or energy rejected by the other company (i.e. residual heat)

	Dewatering synergies	When two entities substitute clean water inflow by residual liquid effluents or industrial water, between them.
	By-products synergies	Raw materials replaced within two entities by the outflow coming from another entity, when the by-product was usually little valorized or either not valorized at all.
Shared Economy	Energy mutualization	Share of investments within two entities that use the same type of energy (steam, compressed air). Scales economies reduces the fix costs, but mutualization also reduces energy consumption in the network.
	Pooling services	When two entities consume or demand the same type of flow, there is an opportunity of pooling supply flows or waste management by achieving financial and environmental benefits. It is easier to negotiate prices with suppliers and optimize transport.
Industrial symbiosis	3-2 heuristic symbiosis	At least three different entities, none of which is primarily engaged in a recycling oriented business, exchanging at least two different products/services related to pooling services, energy mutualization, by-products, water, energy, decarbonization and dematerialization synergies, to enable the recognition of complex adaptive systems (Chertow, 2007).

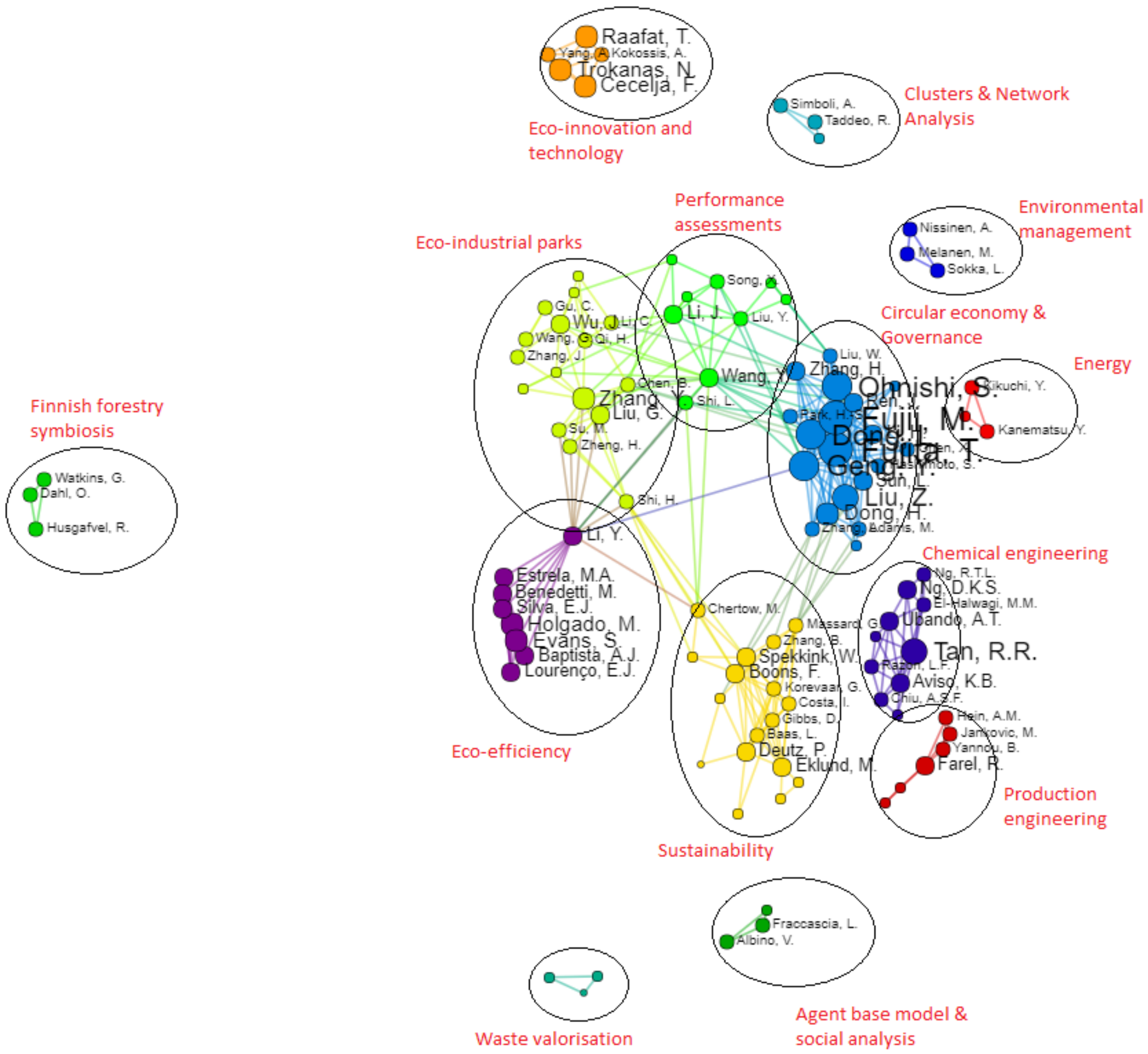
The entire set of strategies described in the Table 1, encompasses the interdisciplinary effort of IE to cope with the paradigm of our current industrial society, where the linear logic of extraction, transformation, production, consumption and waste is threatening the sustainability of the worldwide society. In this study, we bring light to IS strategy, because we conceive it as the most developed IE strategy, encompassing all other strategies from synergies to shared economy projects in a CAS encompassing at least three entities exchanging two products/services. IS entails a perfect field of experimentation in industry able to grasp for a better understanding of the industrial ecosystem dynamic governance in the sought of sustainability (Diemer & Labrune, 2007)(Buclet, 2011). In focusing attention on exchanges of by-products in the industrial ecosystem, the IS attempts to increase the intensity of localized resource use; literally squeezing more value from the same initial inputs through co-located manufacturing processes. This contrast with the recycling approach where the activities focuses on retrieving the materials and goods from post-production consumer phases, by imagining object ends in their design and by seeing ends as beginnings for new objects. IS within interdisciplinary boundaries incorporates methods, research questions and objectives coming from different disciplines from social, natural and applied sciences, which helps to address interdisciplinary challenges like social sustainability.

INDUSTRIAL SYMBIOSIS

Within IE, the epistemology of IS became a relevant issue because it determines the way on which the concept is defined, the boundaries, scope, the methods implemented, the analysis and the social-political implications that outcomes could bring to the current state of the art. To identify the range of approaches in which current literature bears industrial symbiosis, I carry on an extensive bibliometric analysis in the Web of Sciences Scopus®, seeking for all the scientific papers and international reports in English using the word "industrial symbiosis" in the title, keywords or abstract, from 1990 to January 2019. This theoretical analysis unfold 1,385 scientific papers that I further process through a network mapping analysis software called Cortext® Platform. The software runs an analysis over all the authors' co-publications unfolding 14 networks of collaborations within scholars. It was just after I corroborate that those groups are not assembled just based on geographical criteria, that I assume the 14 groups gathered based on the common way they approach industrial symbiosis.

Assumption confirmed after the author's analysis on papers' titles and keywords, finding evidence of shared common research interests, methods and approaches regarding IS, even when those groups assemble different scholars' profiles to integrate complementary research groups, they keep addressing research questions to cope with a common approach of IS. According to the analysis of papers' titles and keywords of each group, I define a name for each one of the 14 categories according to the way they approach IS. It exists a central network of interrelationships in the field encompassed by five different groups: 1) Eco-industrial parks, 2) eco-efficiency, 3) performance assessments, 4) sustainability and 5) Circular economy and governance. The rest of the IS approaches entails different size research networks but barely interconnected between them, impeding their potential to take off in the future. 6) Eco-innovation and technology, 7) Clusters and network analysis, 8) Environmental management, 9) Energy, 10) Chemical engineering, 11) Production engineering, 12) Agent based model and social analysis, 13) Waste valorization and 14) Finnish forestry symbiosis. The entire picture of the central and ancillary networks defining the epistemology of industrial symbiosis is depicted in the Figure 1.

Figure 1. Networks mapping of Industrial symbiosis epistemological approaches



The network mapping displayed in Figure 1, explores which aspects of IS are already attracting substantial attention from scholars, and which ones belongs instead to uncharted territories, then identifying the core of this topic build around: eco-efficiency, eco-industrial parks, performance assessments, sustainability and circular economy and governance. That said, it is also important to stresses the rationale for distinguishing the narrative from the current branches of industrial symbiosis literature. The left side of the core network entails eco-efficiency, eco-industrial parks and performance assessments using quantitative methods such as MFA and LCA. This approach aims to supply data and methodological tools to foster the implementation of synergies (Chertow, 2000) in the eco-industrial parks (Lambert & Boons, 2002). The right side of the main outcome of this network entails sustainability and circular economy and governance, using complex and systemic approaches seeking to bridge the gap between applied and social, producers and consumers, local and global, attracting the academic community attention to the territorial arena (Buclet, 2011) (Ribeyre, Gombert-Courvoisier, & Sennes, 2015, p. 344), where a paradigm shift could be accomplished.

The main problem identified in this study is that even when technical, economic and efficiency issues have been extensively developed in the IS academic literature, there is a lack of assimilation of the social dimension. Despite of the social dimension influence recognition in the industrial ecosystems, the territorial embeddedness and the systemic understanding of the social ecological dynamic has not been extensively developed. ***The main research question addressed in this study is, how to disentangle the complex influence of social and biophysical drivers to accomplish strong sustainability in the industrial ecosystems?*** In Figure 1, we can appreciate that the core of the theoretical foundations and literature applied to give answer to the previous research questions is located in the hinterlands of Eco-efficiency, Sustainability and Circular economy & governance approaches. The theoretical framework in which we base our study, according with this shared motivations and interest, shed light over the CAS analysis and the geographical proximity issue (Hampikian, 2017) of the IS strategy as a subfield of IE.

The assumption that we look forward to validate all along this study is that territorial embeddedness in the IS enhance the emergence and sustainability understanding of the socio industrial ecosystems. In order to validate this assumption we took advantage from a comparative analysis of the socio ecological systemic issues (Hampikian, 2017). In that process, we face three big challenges in the social operationalization of IS strategies: 1) the organizational innovation process among stakeholders. 2) Social and biophysical collective expectancies (reduction of raw materials in the production process, waste disposed decrease and new jobs) (Mirata & Emtairah, 2005) and 3) Policy issues, IS recognition as a social innovative strategy to achieve sustainability (European Comission, 2011).

The understanding of IS as the most developed experience of cooperative innovation within firms needs to cross through the understanding of the iconic example, the experience that shed light over this kind of synergies took place in the 80's in the Danish fjords, with the Kalundborg experience. Representing a turning point of the industrial paradigm, where the only plausible entity in the business management was the firm, disregarding and underestimating the potential contribution of cooperative synergies in local industrial networks. In the Kalundborg case study (Jacobsen, 2008) (Domenech & Davies, 2011) not only the geographic issues were stressed, but also the social and cultural proximity of the actors has been decisive in the integration process (Boons & Howard-Grenville, 2009) explaining its success. Other relevant examples of IS worldwide took place in the port of Rotterdam (Baas & Boons, 2004), in Netherlands (Baas & Boons, 2004), United Kingdom (Mirata, 2004), Portugal (Costa & Ferrão, 2010), Italy (Taddeo , Simboli, Morgante, & Erkman, 2007) and Handelo in Sweden (Martin & Eklund , 2011). Other relevant experiences on industrial branches were also analyzed in the Bio-refinery's symbiosis in USA (Realff & Abbas, 2004), Agricultural symbiosis in Brazil (Ometto, Ramos, & Lombardi, 2007) and the Forest industry in Finland (Pakarinen, Mattila, Melanen, Nissinen , & Sokka, 2010) (Sokka, Pakarinen, & Melanen, 2011).

The concept of territorial proximity was initially developed in France by (Beaurain & Brullot, 2011) this concept explores the mechanisms by which geographical, organizational and institutional proximity encompass the social and biophysical contexts determining the diversity of motivation from social agents (Domenech & Davies, 2011). IS bears the inter-reliant needs between production processes, supplier and disposal activities to every industrial firm, proposing a closing loops strategy for energy, materials and knowledge. 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. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity"* (Chertow, 2007). Industrial symbiosis gives environmental, economic and social benefits to firms involved on this collaborative relationship (Junqua & Brullot, 2015), (Buclet, 2011). In this study, we encompass IS as a subdomain of IE embracing strong sustainability beyond the biophysical definition proposed by Chertow (Chertow, 2000), because we are convinced that social dimension is relevant for its understanding as a social dynamic process reliant on geographical proximity context.

According to the theoretical framework and literature review on what we base our study, and regarding the social aims, we define the IS as a cooperative process engaged by the stakeholders who sought for IE principles application in a local industrial ecosystem, where the will of institutions and companies encourage substitutive or mutual synergies. Therefore, this definition highlights the fact that the accomplishment of strong sustainability[4] in industrial symbiosis is a process; it also highlights the concepts of cooperation (as a choice of business or local governance), proximity, eco-efficiency and resilience as a conceptual framework (Diemer & Morales, 2017). Thus, the socio-economic approach of IS should be framed on the assumption that industry sustainability is drew up throughout the dialectic logic: cooperation/competition, efficiency/resilience, local/global and participatory/authoritarian, emerging from a coherent theoretical framework. Beyond the scope of this study, a question seems essential to feed thoughts for further research studies if we would like to draw up appropriate models to give answer to hot issues like the energy transition or the reduction of greenhouse gases; shedding light over the scale of symbioses issue (local and proximity), where we are convinced that social innovations are essential for the disentanglement of the social process based on ecological, political, cultural and economic aspects.

To cope with sustainability a main driver to encompass IS strategies according to the external environmental contexts and stakeholders is the Governance structure, not only in the emergence (self-organized or planned) (Chertow, 2007) but also during the process, which is barely developed in the academic literature. In order to propose an early stage postulate, that could be further developed in future research projects the governance structure of industrial symbiosis is settled down within two groups: 1) Anchor tenant governance and 2) Decentralized bottom-up governance. This scheme matches the results obtained in our study, and other case studies analyzed in the literature review. The anchor tenant governance steer the industrial ecosystem from decisions motivated by a private actor motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion. The anchor tenant motivation faces economic and market constraints and if the exchanges

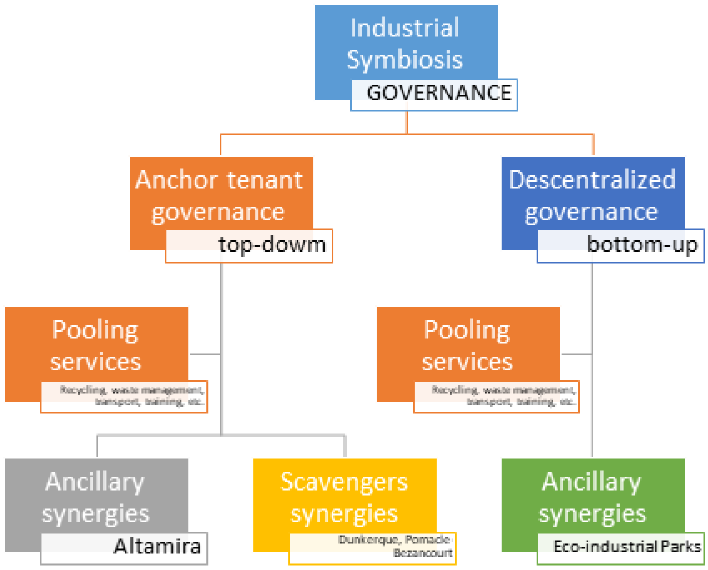
[4] Strong sustainability draw up the essential idea that natural capital is not substitutable, both in the production of consumption goods and as direct provider of utility. It integrates the planetary boundaries concept, postulating that the aim of continue growing in a non-growing planet can only lead to a competition for scarce resources and the exploitation of human labor (Diemer, 2017). (Allenby, 1992). This topic is furtherly developed in detail in the introduction.

succeed, the mutual interest between the ancillary firms that move around the anchor tenant will be reinforced.

The IS projects can be strengthened by post facto coordination, bringing in the scene pooling services, ancillary synergies or scavengers synergies. An interesting research line in this axe is how the cooperation in vertical forward and backward of the supply, production and distribution chain of by-products influences the structural assembling of close industrial networks, working in different activity sectors. Is this cooperation, influencing the transaction costs structure (Yigitbasioglu, 2010), and therefore providing an impact in the vertical acquisition, merging or integration of the SC? The transaction cost theory account for the real cost of outsourcing production of products, including all the costs in the chain, suggesting that (environmental constraints) uncertainty and interdependency can to some degree explain the extent of information shared between buyer and supplier.

The decentralized governance does not entail an economic actor as a kernel of the experience, even if a business association or the public authority takes the steer and the coordination of this experience. There is not an economic stakeholder that gather the ensemble of benefits in the IS, pulling up for the others, even if they hold ancillary benefits. The logic of this relationship is moreover bottom-up, with the network of stakeholders interested in the development of cost reduction, revenue enhancement, or business expansion projects together, with the underpinning spill overs unfolded by an IS strategy.

Figure 2. Typology of governance structure in the IS



OBJECTIVES AND SCOPE OF THE RESEARCH

Concerning the relationships between the IS strategy and the sustainability achievement, two approaches can be disentangled. The first one, state that IS as inseparable from sustainability since the shared premise of environmental and economic enhancement seems to link with it conceptually (Santos & Magrini, 2018) (Boiral, 2005)(Yuriev, Boiral, Francoeur, & Paillé, 2018) and also because of the concepts for reducing natural resources use and improve waste management (Hoornweg et al., 2015). The second concerns the implications of strong symbiosis within a strong sustainable development. The authors argue that with the emergence of strong IS, the IE should acquire a more proactive, critical and interventionist character, conciliating strong sustainability, critical thinking and social complexity.

The objective of this study is to analyze if IS as strategy entails not only the sustainability (Santos & Magrini, 2018), but also encompasses the strong sustainability potential, and for this aim is necessary to provide enough evidence to cope with the complexity of this socio-biophysical mechanism reliant on the environmental conditions (territory) and human actors determinants. The next subsection entitled "Strong sustainability conceptualization", aims to address the strong sustainability struggle, shedding light over the expected objectives of this thesis. Different stakeholders with a diversity of interests, sometimes contradictories are in the quest of interaction with the territory, organizational and institutional proximity as well as the idiosyncratic drivers required in the economic geography for this aim. The embeddedness of this research in the complexity arena is necessary to identify the leading approaches and the future pathways within a systemic proximity understanding of this socio biophysical dynamic.

This research is not looking forward to provide an exhaustive literature review on industrial ecology but to gather some fundamental insights about the IS experience. It is why we choose two case studies to collect a representative sample of industrial symbiosis experiences occurring in developing and developed countries, within different idiosyncratic backgrounds and belonging to different industrial activity sectors. All of them sharing the geographical seaport location, which seems to facilitate the connectivity in between stakeholders and the collaboration in the network even when the synergies among stakeholders are organized differently in Altamira (Mexico) and Dunkirk (France). The diversity in the selection of case studies let us to go deeper in the socio-dynamic of the industrial ecosystem.

The thesis aims to validate the hypothesis of the IS as a strategy for strong sustainability in developing and developed countries, regarding that no general theory of success or failure could be offered, because no such a theory can be expected. Even when we can identify some differences and similarities in motivations, structure and organizations between those categories, the IS is approached as a socio-historical process.

In the case studies, an analytical framework is applied, providing a common ground to better understand the occurrence and functioning of IS, but hardly obtaining predictive power in Altamira and Dunkirk. This study also aims to provide insights for a different assessment of sustainability in the IS, based on four dialectic axes detailed in the theoretical framework (Diemer & Morales, 2017). Introducing a social innovative way to measure circular viability, scale, governance and ecological relationship, bringing about insights from other disciplines such as economy, sociology, anthropology, geography and engineering. This research is not a comparative analysis between different case studies, so it does not look for the generalization of conclusions and assumptions, neither an exercise to provide an exhaustive literature review on IE. But it endeavours a systemic analytical tool that collect IE experiences in Altamira and Dunkirk in the quest of evidence that can support that strong sustainability in IS should not be addressed purely through mechanistic objective methodologies. There is an urgent need to integrate CAS tracking the institutional changes (Ostrom & Basurto, 2011) approach to better understand the social systems dynamic (Lane, 2008) in industry.

Overall, the four auxiliary research questions that we unfold in this research are:

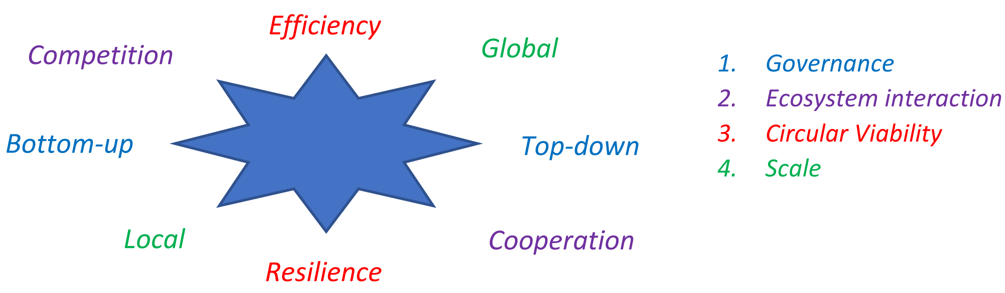
- Why cooperative synergies entail a social innovative strategy to achieve strong and positive sustainability in industry?
- How circular principles could drive sustainability in the local industry?
- How the territory and path dependency influence cooperative synergies in the industry?
- What is the biophysical and social influence of stakeholders' diversity in the industrial ecosystem governance?

For this purpose some methodological resources are engaged in the innovative analysis: both, quantitative like in eco-efficiency and resilience (Fraccascia, Giannoccaro, & Albino, 2017)(Yazan, Romano, & Albino, 2016), and qualitative assessing governance like the complex system analysis (Schiller, Penn, & Basson, 2014)(Meadows, Richardson, & Bruckmann, n.d.) and institutional change (Ostrom & Basurto, 2011), and stakeholders theory (Freeman, 1994) entailing cooperation and proximity (Beaurain & Brullot, 2011).

POSTULATES AND ASSUMPTIONS

The theoretical framework defines the boundaries of this study around the geographic economy, complex adaptive theory, stakeholder's theory, cooperation and ecosystems theory, using IS available tools to understand the drivers (motivations, characteristics, fluxes) behind this cooperative network. Figure 3 shows the four axes (Governance, Ecosystem interaction, circular viability and scale) in the sought of strong sustainability at IS, and they are widely deemed to encompass the behavior and features that take place in the social dimension. Comparing the amount of energy, matter and money that a single firm need if it existed aside from the IS. – i.e. what is the IS bringing to the individual firm, and in reverse, what is the individual firm bringing to the IS.

Figure 3. Four fundamental postulates of sustainability in the IS



Source: (Diemer & Morales, 2016)

There is a well-developed literature review that support the existence of cross-sectional axes of IS (Chertow, 2007)(Diemer & Labrune, 2004) high lightening the symbiotic model developed at Kalundborg (Domenech & Davies, 2011), when other authors have identified the key drivers to a *success story* accomplishment (Buclet, 2011) (Diemer, Figuière, & Prade, 2013). According to Diemer & Labrune (2004), five key drivers became the kernel in the Kalundborg industrial symbiosis emergence: 1) stakeholders collaboration within different industrial sectors, 2) by-products market solution, 3) stakeholders' geographical proximity, linked to ITE, 4) Mutual working and sharing stakeholder's motivation, 5) Stakeholders' communication. Recently (Diemer, Figuière, & Prade, 2013) and (Diemer, 2016) have summarized this idea on what they call the five postulates to achieve industrial symbiosis: difference, economy, geography, psychology and communication.

The first postulate is associated with the idea of strong sustainability applied in the IS is embedded in the Complex systems theory. We assume also that concurrent and heterogeneous components and actors, embedded in a complex ecosystem that seeks to articulate previously disconnected disciplines, regarding the industrial network. Complexity does not seek to gather all knowledge but to recognize the uncertainty existence. We assume that the hole cannot be reduced to the sum of its parts, due to its complexity and also that an open system, is always out of equilibrium, but it could move towards a stabilized dynamism (Morin, 2003).

Highly appreciated by engineers, the industrial metabolism issue turns around the quantitative accounting (flow and stocks) of physical and economic values in the industrial system (Ayres & Ayres, 2001). In the book entitled *Changing course: A global business perspective* *on development and the environment*[5], Stephan Schmidheiny in collaboration with the WBCSD developed the industrial metabolism' methodology closely related to the eco-efficiency principles. According to Suren Erkman, this method consists on "mass balance, material flows and stocks account, outlining complex and dynamic pathways" (Erkman, 1998). In most firms, industrial metabolism triggers in the form of input-output matrix and LCA. Industrial metabolism makes material flow's control possible, measuring the physical exchanges and defining the contextual structure (Esquissaud, 1997). From an economical point of view, industrial metabolism includes all the material and energy exchanges letting emerge a better understanding of the system's behavior (Hertwich, 2005).

The second postulate based on the ecosystems theory push forward some assumptions framing the rational boundaries of the ecosystem around product/service supply chains. Supposing the cross sectional analysis of time as a required criteria of the dynamic evolution analysis in ecosystems, therefore imbricating the existence of behavioral and decisional patterns (Barbault, 2013; Hess, 2009). Concerning sustainability, we also assume that we have a limited stock of biophysical available resources in the planet and according with the strong sustainability framework the allocation of capital (economic, social and natural) are not substitutable between them, bringing on board the carrying capacity the planetary boundaries concept and the issue of ecological scarcity.

IS encourages cooperation, or at least act as a transition gateway where bilateral or multilateral relationships usually keep regulated by market competition. IS is also defined by proximity looking to reset local economy, throw the systemic feedback drivers (Colin, 2011). In this study, the IS analysis is based on the assumption that local connectivity in the IS unfolds the potential to attract or create innovative activities, acting as a vector for sustainability. IS synergies takes place in a market competitive environment, without disregarding the efficiency constraint. In the IS, the ecological metaphor encourages market relations based on synergies between stakeholders who prefer to encourage cooperation without disregarding competition. The IE inspires relationships between living organisms in natural ecosystems (positive relationships interact together with antagonistic relationships). For example, competition, amensalism, predation and parasitism are favorable if they contribute to the overall wellbeing of the

[5] This is a report presented at the UN environmental assembly in 1992 at Rio de Janeiro.

ecosystem, even though commensalism, synergy, mutual aid, cooperation and symbiosis could represent a problem if they are overloaded and disproportionate. Strong sustainability in the IS refers to a paradigm shift, the understanding of hot social issues as complex questions. What could be positive in a specific context, overlap some rebound effects if it is not well managed after certain threshold. The illustration of the synergetic relationship in the industry is the model based on the exchange and sharing of goods, services, time and knowledge between actors. The second example displays the cooperation relationship to produce dual solutions for goods and services according to: (i) moving from the sale of goods and services to a contractualization of values of use, (ii) systemic approach to take into account negative externalities (biophysical or social).

Table 2. Relationship typology in the Industrial ecosystem

Indifference relationships	**Antagonist relationships**	**Positive relationships**
Neutralism: absence of any association or antagonism between species that coexist in the same environment. Synecie: two partners regularly associated without one being source of advantages or disadvantages for the other.	Competition: a struggle for limited resources. Amensalism: some living beings use toxic substances to fight against their rivals. Predation: the use of a living being by another organism to feed on it. Parasitism: the use of a living being by another organism to feed or reproduce without inevitably causing death.	Commensalism: an association that benefits only one of the two associated living beings, who can hardly live without the other to whom it is indifferent. Synergy: the stimulation of the activity or development of a living being by the presence of another. Mutualism: allows many living beings to associate with each other for mutual benefit. Symbiosis: is the most advanced form of association between living beings because the protagonists benefit from mutual benefits and could not survive, or very badly, out of this union.
Firms can help each other in industrial ecosystems, without paying attention to others performance (complementary activities). Illustrated by an eco-industrial park.	At the industrial ecosystem, the competition is more intense as more participants are challenging each other competing for a share of the market if they play in the same industry and	In an industrial ecosystem, outsourcing activities is like commensalism, because the survival of the outsourcing firm depends on the client. Platforms and clusters are good metaphors of synergistic relationships. Corporations, cooperatives and joint venture belong to Mutualistic approach.

	target the same clients. Merging and aggressive spin-off strategies are usually developed.	Symbiosis is the ideal type of associative process. Encompassing resources, knowledge, capital ... and skills in the sought of a symbiosis within stakeholders.

The third postulate comes from the economic geography field, where we apply some assumptions like the fact that proximity is not only defined by the Euclidian distance, but by the organizational and institutional proximity within stakeholders. Local governance influences the spatial differentiation and uneven development, through path dependency. Indeed, we assume that organic networks present always positive and negative features, recognizing the actors' diversity that determines the rationality of decision-making (Beaurain & Brullot, 2011; Beaurain & Varlet, 2014, 2015).

Although IS is based on territorial stakeholders' proximity, the territory is considered as the functional space where local issues take place (waste transformation, water purification, depollution of industrial sites, etc.). The proximity principle is introduced as a key postulate regarding distance in economic terms (transport cost, infrastructure needs) and institutional distance (communication, confidence, discussions and meetings). The territory encourages new forms of cooperation within stakeholders contributing to the resurgence of shared interest between stakeholders in the same territory (coherence territorial schemes or agendas 21). IS become a strategy to bridge the gap in the ITE, building a common ground to promote the idea of sustainability. According to (Buclet, 2015, p. 16), Urban ecology (Kennedy, Baker, Dhakal, & Ramaswami, 2012; Ometto, Ramos, & Lombardi, 2007) and industrial ecology (Beaurain & Varlet, 2015; Decouzon, Maillefert, Petit, & Sarran, 2015) gave birth to territorial ecology, bringing the industrial metabolism methodology from those disciplines (input/output approach). The governance issue when applied to IS needs to be associated with behaviors, rules, decision-making, assessments and control panels that enable its correct operation.

The fourth and last postulate assumes that IS is embedded into an economic-political-ecological-cultural system, where the role-played by public authorities needs to be emphasized. State, regional councils or local authorities unfold governance when 1) enforce the accomplishment of policies, norms and rules within the operational dimension (i.e. water decontamination, CO_2 reduction, pollution thresholds). 2) Guarantor of shared values (justice, tolerance, respect, etc.) 3) Steer the territorial strategies (stakeholders familiar with the environment and institutional reality are able to encourage participation and create social innovation). The systemic understanding of stakeholders' dynamic clarifies the understanding of the symbiosis and endeavors formal and informal communication, unfolding conventions and agreements. Finally, social dimension (job creation, social trade-offs and services, civil society involvement, delays, information and participation in decision-making) accomplish the development of the strong sustainability approach in the IS only if they spur social acceptability.

We assume that these four postulates reinforce the strong sustainability of the IS and further research should be encouraged in this line to develop (quantitatively and qualitatively) indicators[6] able to measure this sustainability achievement. The conceptualization of sustainability is based on the four pillars of IS theoretical framework (Diemer & Morales, 2016) and to present an innovative way to measure them (Fraccascia, Giannoccaro, & Albino, 2017) (Yazan, Romano, & Albino, 2016), borrowing insights from other disciplines such as ecology, economic geography and engineering. The few previous studies on sustainability of IS have been analyzed in terms of resilience or eco-efficiency techniques applied to an industrial context, but not through both of them. The proposed study aims a methodological tool used to assess sustainability through different quantitatively and qualitatively methodologies according to the context and research question asked in every different case study analyzed in Altamira and Dunkirk. SD, ecosystems theory and complex theory as well as resilience (diversity and redundancy) and eco-efficiency have been introduced in our study to feed the critical analysis.

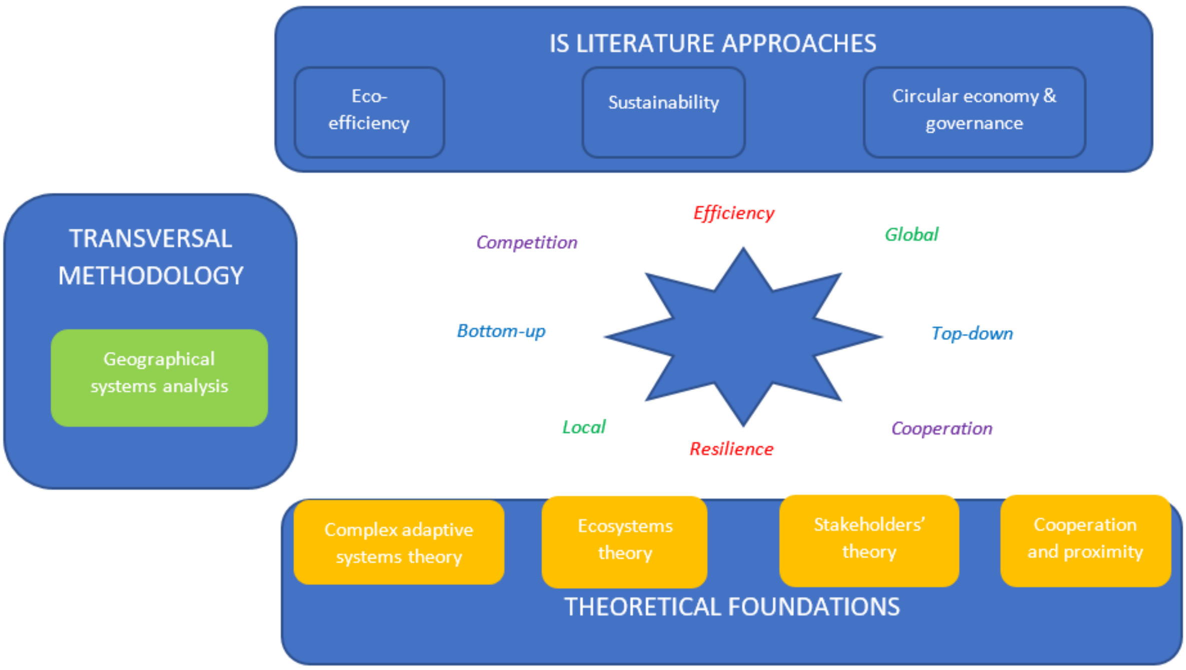
The theoretical framework is build up in the hinterlands between Eco-efficiency, Eco-industrial parks and Circular Economy and governance approaches (Figure 1). The available toolbox provides a theoretical body that seems to be concrete enough to identify and analyse some occurring and functioning drivers of sustainability in the IS. The integration of biophysical and social dimensions in the IS analysis is not new, but what represents the novelty of this study is the opportunity it provides us to integrate both dimensions into a territorial interpretation, where the geographic system dynamic methodology enables the

[6] This study is currently on work in the frame of the Manuel Morales's Ph.D. dissertation.

clarification of stakeholders' behavioral patterns, unfolding the human motivational causality and the network; stressing the fact that those interwoven links operated by power/cooperative relationships could spawn a distortion in the by-products market if the governance is not strategically defined. The previous distortions and unbalance between resilience (diversity and redundancy) and eco-efficiency represent a hinder to the strong sustainability in the long-term.

Some unanswered questions in the field of IS are unfolded in this dissertation through a broad understanding of geographical proximity and extending the discussion about the SD approach through a CLD identifying key drivers for each stakeholder's behavioral patterns in the IS (Bennich, Belyazid, Kopainsky, & Diemer, 2018). The theoretical framework also handles well the complexity of territorial influence, incorporating to the discussion that they are at the same time strongly influenced back by the industrial system, shedding some light on the territorial embeddedness of IS studies (Berkel, Fujita, Hashimoto, & Geng, 1997).

Figure 4. Theoretical framework applied to IS analysis



The Figure 4 presents the concept and literature we use to institutionalize IE as a normative framework to improve the understanding and application of IS as strategies for strong sustainability. We present the theoretical framework composed by the CAS theory, Ecosystems Theory, Stakeholder's Theory, Cooperation and Proximity Theory displayed in yellow boxes; regarding the three IS approaches (blue boxes) on which the study is build: Eco-efficiency, Sustainability and Circular Economy & Governance, according with the bibliometric analysis stated in the Figure 1. Addressing the transversal Geographical systems analysis methodology in the core of the analysis; the circular viability axe (in red font) which entails efficiency and resilience; the scale axe (in green font) which encompass the local and global positions. Followed in the third place by the Governance axe (in blue font) including the Bottom-up and the Top-down sides, as the governance stewardship, if steer by the firms engaged through a participative strategy, the governance model is known as bottom up scheme, but if public authority or an anchor tenant centralizes the governance then is known as top-down scheme. The ecosystems interaction axe in purple entails competition and cooperation. Looking forward to include the geographical proximity understanding into the social biophysical dimension of IS, thus improving governance and relationships through proximity.

Finally the transversal methodologies that we use in the study to answer the research questions and verify the hypothesis are the Systems Analysis and the Interdisciplinary displayed in the green boxes. The overall research question addressed in this study is how to disentangle the complex influence of social and biophysical drivers to accomplish strong sustainability in the industrial ecosystems? Indeed, four auxiliary research questions were displayed all along the seven chapters that compose this dissertation with the aim of supporting the way we answer the general research question, previously enounced.

Figure 5. Auxiliary research questions and the related chapter that gives them answer

Paper No.	Title	Theoretical framework	Research question tackled
1	Could Industrial and territorial ecology become a strong sustainable model for developing countries? Depicting Tampico By-product case study in Mexico	Economic geography and Sustainability	Why cooperative synergies entail a social innovative strategy to achieve strong and positive sustainability in industry?
2	Servitization in Support of Sustainable Cities: What Are Steel's Contributions and Challenges?	Sustainability, Complex Systems	How circularity principles could drive sustainability in the local industry?

3	Analyzing Symbiotic Relationships in Sustainable Cities - A framework	Complex Systems, Ecosystems theory	Why cooperative synergies entail a social innovative strategy to achieve strong and positive sustainability in industry?
4	Who gets the benefits from an industrial and urban symbiosis? An embeddedness analysis in a sustainable city ecosystem	Cooperation, stakeholders theory and Sustainability	How the territory and path dependency influence the cooperative synergies accomplished in the industry?
5	"By-Product Synergy" changes in the Industrial Symbiosis Dynamics at the Altamira-Tampico Industrial corridor: 20 years of industrial ecology in Mexico	Complex Systems, Ecosystems theory and Economic Geography	
6	Altamira's understanding of the territorial context through eco-efficiency and resilience	Complex systems, Dialectic theory, Efficiency and Resilience	What is the biophysical influence of stakeholders' diversity in the industrial ecosystem governance?
7	Dunkirk industrial systemic governance understanding through a geographical proximity approach	Complex systems, Ecosystems, Economic geography	What is the social influence of stakeholders' diversity in the industrial ecosystem governance?

THEORETICAL FRAMEWORK

The theoretical framework entails the Complex adaptive systems theory, the Ecosystems theory and the Stakeholders' theory, paving the way to the application of the Geographic system dynamics. The set of assumptions on what we base our theoretical foundations encompass the IS social dimension understanding and modelling.

1) Complex adaptive systems theory

Science should be objective and avoid bias, but when academics increase focus in some tools because wide knowledge accomplished, then the tendency of tool adeptness became relevant and supply some biases to our theoretical foundations. Therefore, science hold up by scientist does not always pick the best methodological choice from the available toolbox to treat a specific research question, usually disregarding the expected scope, scale and complexity in the process, thus, resulting in a smart but not wise science. The early beginnings of the complexity analysis in social sciences can be identified back hundreds of years ago, with the Wealth of Nations (Smith, 1776), representing one of the most cohesive and complex discussions of the economic allocation issues. One of the economic theory kernels has been the "invisible hand" leading the self-interested agents into well-formed structures, independent from any single agent's intention (Miller & Miller, 2007); furthermore, defining the boundaries of the social disorganized complexity and the feedbacks available for tuning the performance of complex systems through organized structures. Since the second half of the XVIII century with the invisible hand theory until the end of the XX century very little happens in the complex adaptive analysis in science. Indeed, it was over the last two decades that new tools and ideas emerge in a new world of scientific possibilities for understanding complex adaptive social systems.

The end goal of science is to make the wonderful and complex understandable but not less wonderful, with this in mind the CAS theory organize a toolbox with the potential to integrate structural complexity analysis (Patrucco P. , 2011) (Patrucco P. , 2009) encompassing the social and biophysical dimension in an interdisciplinary way. The theory of complexity is systemic and dynamic by itself, and has been recently applied to a diversity of fields and interdisciplinary research questions, like the climate change complex adaptability (Roggero, Bisaro, & Villamayor-Tomas, 2018), the institutional change studies (Ostrom & Basurto, 2011), but it has barely discussed the complex adaptability of IS. The CAS in the IS became an insightful object of study, where very little has been done, with some exceptions in the understanding of organizational forms (Walls & Paquin, 2015), networks (Schiller et al., 2014) forms within companies and knowledge (Mauelshagen et al., 2014) exchange. In a broad the complex adaptive analysis of IS embedded in a territory has not studied with the lenses of social dynamic analysis of industry as a heterogeneous set of actors that interact with the objective of changing the organizational structure and the activities planned over time.

Furthermore, an analysis of the complex systems' assumptions in the IS helps us to identify the causality in the structure and the potential mechanisms engaged to reinforce or balance the behavioural patterns. The set of assumptions could be summarized in the following three points: 1) within complex systems, the actors are heterogeneous, especially in relation to their skills and knowledge, without disregarding the fact that complexity accepts uncertainty by theoretical definition. 2) As a consequence, the actors only have access to a limited part of the resources and the creation of new collaborative structures occurs through trial and error of the processes of the individual and social behavior of the system. 3) The interaction between heterogeneous actors is fundamental in this context, because only through this the actors can access new skills and modify their behaviors. Interactions raise based on adaptive reciprocity between individuals and their environment pushing forward the transition to new functional models.

The industrial ecosystems represent complex systems where transition phase takes place (Durlauf, 2005) outlining large changes by small individual changes – simplification in a complex system would lack the properties of the system, precisely because the system cannot be reduced. Thus, the use of methodologies as system dynamics, circles of sustainability in this study bears in the potential management of complex systems, and the feedback integration into the structural analysis, that keeps the system updated. For example, firms' instability to face disruptive changes in the market could affect the others stakeholders' behavior, potentially triggering its departure, and therefore modifying completely the industrial ecosystem structure.

2) Ecosystem theory

The ecosystems theory calls the attention from the international scientific community, widely used in social sciences, business management and hard sciences, setting the benefits coming from its application in pragmatic situations (Tsujimoto, Kajikawa, Tomita, & Matsumoto, 2017) (Morales, Diemer, Cervantes, & Carrillo-González, 2019). Here we present the five main contributions of ecosystems theory (Nielsen, 2007) in fields others than ecology: 1) the ecosystem concept analyses positive but also negative properties in organic networks: trophic competition, depredation, parasitism and destruction of the ecosystem. 2) Each actor in the ecosystem has different motivations and objectives, defining the logical decisions taken that could trigger unexpected effects in the ecosystem. 3) The ecosystem boundaries are defined by the supply chains structure; making no sense to limit the analysis to political boundaries. 4) The ecosystems theory enables a dynamic analysis of the stakeholders engaged in the SC. 5) The main issues of ecosystems research are the behaviour and decisional patterns identification, reinforcing or hindering sustainability within the industrial ecosystem (Tsujimoto et al., 2017).

We define ecosystem as "a biological community of interacting organisms and their physical environment". In a broader sense, the ecosystem is also considered "a complex network of interconnected systems" (Oxford Dictionary, 2019). Industrial ecosystems was the kernel of IE field (Erkman, 2004) (Ayres & Ayres, 2001) (Durlauf, 2005) (Frosch & Gallopoulos, 1989) bringing ideas from other fields and further methodologies with the aims of complexity analysis in sustainability. Thus, we can state that industrial ecosystem is not only a concept framing a new discipline but a strategy of social complexity with the aim of foster stability, resilience, eco-efficiency and proximity in the long term.

3) Stakeholder's theory

Managers stands out that in order to balance the interest of the stakeholders involved in the ecosystem is necessary to study the stakeholders' network of interactions. I identify in the literature four ways of approaching stakeholders' relationships: optimizing, balancing, and structuring. During the dissertation of this study, we stand out only two of this approaches: balancing and structuring. The balancing approach of stakeholders' theory starts from the idea that you cannot have it all, and facilitate the decision on how to share the pie between different stakeholder's holding different objectives and motivations, dealing with contradictory pressures in the industrial ecosystems, such as standardization/diversity; control/autonomy; efficiency/resilience; cooperation/competition; individual/collective, among others (Diemer & Morales, 2016). The structuring approach deals with stakeholders by increasing the understanding of stakeholders at hand. This approach assumes that there is a lack of relevant knowledge available, takes one-step back, and focuses on learning more about the problem. The logic behind this approach is that by obtaining a better understanding of the problem, the researchers are able to facilitate their balancing. Methods available include discrete event simulation (DES), soft systems methodology (SSM) and system dynamics (SD).

The SD analysis is one of the main contributions of ecosystems approach to industrial ecosystems understanding, encompassing stakeholders' values and motivation understanding. The dynamic analysis cannot be understood in a static way, since the industrial network always changes, in the sought of mechanisms and behavioral patterns identification, that can implement strong sustainability, according to the definition framed in (Diemer & Morales, 2016).

The major issues identified in the stakeholders theory are: the instrumental versus moral stakeholders objectives; the focus on trade-offs versus the focus on avoiding trade-offs; and the focus on the decision-making organization versus the stakeholders engagement (de Gooyert, Rouwette, van Kranenburg, & Freeman, 2017). These three dilemmas frame the large body of knowledge known as "stakeholders' theory" that consists on simultaneously taking the interests of multiple stakeholders into account (Freeman, 1984). Freeman participate in the articulation of the stakeholder's theory in the 1960's, as a philosopher Freeman encompass the stakeholder idea into a managerial framework, giving birth to the so-called Stakeholder management (Freeman, 1984). Insights from decision theory and game theory were widely incorporated in Freeman's Strategic Management: A Stakeholder Approach where he picture up the history of stakeholders' concept, looking forward to develop the early decision oriented framework in stakeholder's management. In opposition to what its name suggests, stakeholder's theoretical framework does not refers to a single theory, or even a narrowly defined set of assumptions, rather it refers to a "genre" of empirical and theoretical studies underlining the stakeholders strategic influence.

Indeed, in this study we are going to highlight the conflict existing between the decision-making objectives of stakeholders' theory versus the engagement aims, where the importance of misperceiving stakeholder interests led to relevant discussion in this analysis. Complexity in the stakeholder's relationship stands out that participatory processes are necessary to obtain the stakeholders' engagement. Engagement can help to build lasting and mutually beneficial relationships (Maggioni & Santangelo, 2017) and that it may result in higher financial returns (Hein et al., 2017). The level of engagement depends on an organization's consciousness, ability, willingness, and interests.

The business framework applied to IS asks to look at this business network as a set of stocks in a portfolio, with a selection and nourishment given to winners and the door given to losers. The external dimension is usually called "Industrial Attractiveness" in the industry and is usually measures by the productivity rate of the industry under consideration. We call the internal dimension as "Business strengths" and we measure them through the internal available instruments.

Stakeholders are the only possible agent of change in the industrial ecosystem, figuring out the available pathways of social structure, the business rules and encouraging innovation for a sustainable industrial flourishing. The role that stakeholders play (Freeman, 1984) in the industrial ecosystems include the strategic steer of industrial dynamic mechanisms, in the quest for a sustainability enhancement through a critical analysis of complexity. When an ecosystem is managed strategically (Tsujimoto et al., 2017) it is possible to trade off the imbalances with its environment towards a stabilized dynamism. For example, when analyzing renewable energies, smart cities, innovation and technology through a systemic methodology, the stakeholders' interactions are included into the analysis, in order to avoid an oversimplification of the analysis taking into account only the unidirectional cause-effect relationships (cost reduction, productivity, efficiency, etc.).

The stakeholder's relationship network has already been considered in the literature, but not with a geographical SD approach. While there is a broad body of literature about IS and stakeholders collaboration, which may eventually change the system on a broader scale, the literature about stakeholders' systemic analysis and the role of proximity in industrial ecosystems are relatively scarce (see Hein et al, 2017; Beaurain & Brullot, 2011; Beaurain & Varlet, 2014). While the collaborative economy is closely linked to social economy (Defalvard & Deniard, 2016), ITE gave birth to a fertile ground for industrial symbiosis experiments in developing countries. Indeed, IS can take the form of a decentralized cooperation strategy (Berr & Diemer, 2016), pooling of resources, social sharing or donation, a better management of natural resources and energy. Stakeholders' clear communication (Freeman, 1994), (Dosse, 1995) in the local governance implementation involves 1) the identification of different mechanisms and systems that coexist (capitalistic firms, associations, cooperatives, public authorities, etc.); 2) understanding of sustainability policies operation and assessment (ecological, political, cultural, economic). Finally, 3) the exploratory scenarios of IS in the sought for sustainability.

4) Proximity and Cooperation

Spatial economy attempts coordinated effort to optimize territorial economic and political resources; fundamental to the social understanding of IS structure. The dynamic evolution of the industrial network, which evolves in a complex environment, does not allow the firms involved in by-product exchanges to calculate their optimal geographical localization for suppliers and consumers by traditional linear methods. New methodologies in the field of geographical proximity unfold analytical tools that facilitate the complexity analysis in a local scale, triggering the decision-making procedure between producers, consumers, and institutions. The dynamic geographical proximity approach encompasses two different complementary dimensions of proximity: spatial proximity defined by Euclidian distance, and relationship proximity, defined as organizational/institutional proximity which refers to the interwoven network of relationships beyond the physical space (Beaurain & Brullot, 2011).

The geographic and spatial economy literature has influenced the analysis of IS (Chertow, 2007), encompassing a geographic territorial analysis that enables the complex analysis. The by-product synergies and the participation of local authorities in waste management and recycling denote strong engagement of local geographical dimension in IS. The literature reviewed by Jedelhauser and Binder (2018) reveals that the vast majority of geographically oriented stakeholder analysis is embedded in social-biophysical structures, and these specific contexts enable or hamper economic coordination strategies within stakeholders in the industrial ecosystem. In comparison with the market economy, the cooperative economy has some advantages for IS: 1) consumers are also producers; 2) stakeholders are involved at all stages of the process; 3) relocation generates new synergies; 4) dematerialization can boost the economy of functionality (value of use); 5) pooling (mutual ownership) can change individual property.

TRANSVERSAL RESEARCH METHODOLOGIES

System dynamics entails concepts such as feedback information flows and stock variables to model social systems and explore their relationship regarding behavior changes over time (Forrester, 1961). System analysis could entail SD studies addressing complex problems using a set of assumptions from mental models. We stand out from the assumption that the reality modelling is not possible, even though what we seek is to model the social mental models that we have about a certain issue, with defined boundaries. In SD we base our scenarios in representation of some aspects observed in our reality, so we can say that these models are the product of the interpretation of this set of observations and internalized experiences. We define the MMDS, as the social mental models that build the assumptions on which the systemic model is encompassed, given that the behavioral patterns of each stakeholder influence the structure and performance of the system, a fully description of the concept is developed in Chapter 3.

Indeed, the polarity of each feedback flow is crucial for the understanding of the behavioral model, where the disruption of one loop can result in a reinforcing effect (positive polarity) or a balancing effect (negative polarity), therefore counteracting or resisting the direction of the original flow. The role of simulations in SD is to understand the consequences of relationships and expose behaviors that may become counterintuitive in the model.

SD is a methodology developed for non-linear problems analysis that can be struggled by the integration of behavioral patterns reinforcing or holding out the industrial structure through feedback effects. Since the publication of *Industrial Dynamics* (Forrester, 1961), *Urban dynamics* (Forrester, 1970) and *Limits to growth* (Meadows,, Meadow, Randers, & Behrens III, 1972) the use of SD to study managerial issues through complex models gain attention within scholars. SD enables a better understanding of feedback flows and stock variables to structure the social industrial systems. The historical analysis of IS over time let us understand the behavioural changes in the ecosystem (Forrester J. , 1961) (Forrester J. , 1970) based on four main features of a dynamic system: (1) It define boundaries around the system, (2) Feedbacks interconnect structural elements within the limits. (3) Stocks provide quantitative information within feedback loops. (4) Delay gives an idea about the feedback's time lag coming from physical, administrative or technical source in the system.

One of the most important insights introduced by the systemic framework is the fact that all actions can be followed through feedback cycles. Therefore, it is relevant to be able to disaggregate the system in small-interconnected parts and analyze its behavior as integral system. The feedback loops interconnect the system in a CLD aggregating the small parts that encompass it, feeding the system with the existing biophysical and social information, and thus, influencing back the future decision-making. We used to think about cause and effect relationship in one direction, but when we talk about the action A that causes the result B. We should not forget that B represents a new condition of the system that changes forward the future structured by itself (Forrester, 1961).

In general, SD studies begin with the complex analysis, including a set of assumptions used to describe this situation. These assumptions act as MMDS, defining the polarity of each feedback flow, which is essential for the understanding of industrial ecosystem because a disruptive relationship can intensify the original effect, assuming the consequences of feedback relationships and revealing some counterintuitive behavior, according to the model. Two main methods that help to visualize those concepts within the academic community are the CLD and the SFD.

STATE OF THE ART

Since the 20th century many IE experiences have been worldwide spread, their implementation in specific territories concern the technical, economic, informational, organizational, infrastructure and normative dimension understanding and internalization (Duret, 2007) (Orée, 2013). Even when IE imports their seminal theoretical framework from the scientific ecology, the methodologies and scopes currently applied; let us see that social behavioral patterns are desirable for a better understanding of the industrial ecosystem dynamic, betting on a systemic approach of the social dynamic of industry (Ayres & Ayres, 2001). IE seeks beyond the firm's individual actions in the sought of eco-efficiency, entering to geographic analysis of case studies to give them a territorial dimension (Buclet, 2011). The IS is presented as one of the means to reduce the impact of industrial activities on the ecosystem, through cooperation between companies and local authorities, particularly at the level of territories. Therefore, IE stresses stakeholders' synergy between actors relatively close geographically, but missing the opportunity to exchange, lack of common interests (Diemer, Figuière, & Pradel, 2013). The field of ITE is thus, defined based on the importance devoted to the territorial actors (local communities) and the interaction flows (urban ecology and metabolism).

The way we approach IS in this study is based on the socio ecological perspective joining sustainability and governance issues, unfolding simultaneously the needs for an interdisciplinary theoretical framework. In the literature review we found some studies using

SD (Forrester J. , 1970), the stakeholder theory (Freeman, 1994), complex thinking (Morin, 1973) (Morin, La Methode, 1977) (Morin, 2003), and the theory of institutional change (Frosch & Gallopoulos, 1989) (Ostrom & Basurto, 2011), that shed light on the importance of the systemic understanding of the industry as a dynamic process. We are convinced that IS' social innovation strategy would then be able to inspire the strong sustainability paradigm shift in industry at local scale (Metereau & Figuière, 2015, p. 221).

There are three essential problems identified in the IS according to the literature, the first one is the internal inefficient use of energy, materials and information in the companies, and the underpinning relationship with the further quantity and quality output. The uncertainty in the quality and quantity of the by-products output represent a risky variable that hinders the IS's success in many cases, because firms hinge on competitiveness and market efficiency. Inefficient use of resources could threaten the IS continuity, unfolding a symbiotic flow rearrangement or, in the worst case, the IS structural change due to a firm departure, triggering a potential disruption for the network. Economic benefit is the main driver for symbiotic relationships as Chertow shows in (Chertow, 2007), stating that any disruption or reduction in economic benefits may be sufficient to interrupt the symbiotic flow or, in the worst case, force the departure of a firm in the network (Mirata, 2004).

The second main problem identified in the literature review is the vulnerability or the lack of resilience (Ruth & Davidsdottir, 2009), triggering shortcomings to the economic, environmental and social benefits resulting from IS, may jeopardize symbiotic fluxes or, in the worst of cases, push them to leave out of the network (Mirata, 2004). The third concern is the IS governance disconnection with the scientific literature, far from been understood as an institutional, economic and cultural phenomenon triggering normative and prescriptive positions (strategies, policies, action plans, etc.). Governance and management are complex drivers that cannot be understood if disregarding the practitioners' advice and experience; therefore, we need to take some distance to see the whole picture (as institutional, social, economic and cultural phenomenon). The normative and prescriptive realm has to be included in the analysis with an interdisciplinary approach integrating territorial embeddedness analysis (local economy, scale economy, local development, etc.) and social sciences (embedded in cultural changes and very often associated with economic behavior).

Costa & Ferrão (2010) gives food for thought on the importance of favorable governance for the development of IS «*shaped through an interactive process wherein the government, industries and other institutions are guided towards aligning their strategies in support of collaborative business strategies*». Pushing forward the 3-2 heuristic logic definition (Chertow, 2007), paving the way towards an open discussion on the relationship between resilience and effectiveness (Diemer & Morales, 2016). We take as worthy insights the historical analysis developed by the authors in the Chapter 5, setting up four evolving phases of the IS: emergence, regional efficiency, regional learning and sustainability of industrial district (Boons, Spekkink, & Mouzakitis, 2011)(Morales, Diemer, Cervantes, & Carrillo-González, 2019). The historical understanding of this studies let us incorporate relevant parameters as the number of stakeholders involved in the IS, potential synergies of material and flow and the total amount of companies involved in the network. In despite of the aggregation of this information it helps us to build the process of the dynamic structural behaviour over time, even if this information is not available in a disaggregated form by firm.

Table 3. Industrial Symbiosis' transition phases of development

Dynamic Phase	**IS type**	**Motivations**	**Initial actors**
Emergence (1997-2006)	Facilitator - brokerage	Interfirm organizations and transparency	Public authority facilitator or Business Council
Regional efficiency (2007-2010)	Facilitator collective learning	Eco-efficiency and environmentally friendly practices	Firms association
Regional learning (2011-2015)	Facilitator collective learning	Resilience	Pivot firm
Sustainability of industrial district (2016 up to now)	Eco-Cluster development	Adaptability and flexibility	Business council members, external experts, practitioners and local authorities

STRONG SUSTAINABILITY CONCEPTUALIZATION

The linear (growing) economic model is incompatible with the planetary boundaries, because it is obvious that a model requiring growth in a non-growing planet can only lead to a fierce rat race and ruthless competition for scarce resources and the exploitation of human labor (Diemer, 2017). Therefore the weak sustainability goals attended by the IE focused on technical solutions (Allenby, 2000) that expect to allow the industrial economy to continue growing in a "sustainable" way, indicates that "sustainability" of the industry is still considered more crucial than that of the planetary ecosystem on which human life depends (Aigner, Lovell, & Schmidt, 1977) (Baas & Boons, 2004).

A main part all along the dissertation is the meaning we give to sustainability in the IS framework, we define it as the set of practices and meanings of human engagement that make for life-world that project the ongoing probability of natural and social flourishing, vibrancy, resilience and adaptation in the industrial ecosystem (James, 2015). We use the concept of social in the study in a holistic perspective (James, 2015) trying to bring the "social" into the center of the contention, displacing economics as the focus of all understanding while still taking it seriously. For this purpose, social encompass the ecological, political, economic and cultural dimensions, leaving aside the academic debate about the anthropocentrism or biocentrism. We do not seek to go further in the reflection about the genesis of the paradigm transition to achieve sustainability in the industrial ecosystem because we agree in the fact that both of them could be possible and the existence of one does not discredit the existence of the other. The Biophysical and the social realm need to be considered through holistic and systemic strategies towards better scenarios in industry.

To better understand what strong sustainability concept brings about as new insights, we need to understand that the Weak sustainability can be interpreted as an extension to neoclassical welfare economics (Daly, 1991). It is based on the beliefs that what matters for future generations is only the aggregate stock of "human" and "natural" capitals. According to weak sustainability, it does not matter whether the current generations uses up non-renewable resources or dumps CO_2 in the atmosphere as long as enough ports, roads and machines were built in compensation, because natural capital is regarded as essentially substitutable in the production of consumption goods and as a direct provider of utility. The debate is currently defining the boundaries and scope of what strong sustainability brings about, if triggered in a complex system like the industrial one. Since the beginning of this debate, seems that the IS strategies applied in a territory corresponds with the definition of strong sustainability, therefore the synergies escape from the market logic, on which the price is clearly the only determinant of the consumption and demand volume (other drivers considered in the theory as externalities).

In the IE literature is important to make the difference between weak and strong sustainability. The weak sustainability is coined by the vision of B. Allenby, a very positive and scientific thinking concerning the material and energy exchange flux in production and consumption systems. This relationship is the most developed at the IE literature and trigger two kinds of postulates: "technological determinism" and "traditional liberalism", and it promotes a cyclical functioning to maximize the materials and energy flow within the industrial system, thus no waste is rejected and the energy needs to be supplied exclusively by the solar energy. In that sense, the IE is understood as the "science of endurance" to which it is enough to have good engineers in order to shift the industrial society into a circular ecosystem (Beaurain & Brullot, 2011). The IE based on this definition of sustainability does not correspond to fundamental principles of sustainability due to the lack of coherence and weakness of their assumptions, creating a gap between the technical and social aspects.

The strong sustainability paradigm shares some values with the weak paradigm as the necessity of cyclical ecosystems functioning but it also highlights differences as structural and organizational features of this analogy with the natural ecosystems. J. Ehrenfeld states that human issues are the kernel of the IE, because the assumed perfect market conditions are never or almost never present in the reality due to the imperfect use and diffusion of information, turning the stakeholders' economic behavior into an oligopoly. The strong sustainability highlights coordination, communication and information exchange as the main structures holding the transition to a new industrial ecosystem. The vision of sustainability that we are holding on this study aims to encourage and embrace the "Strong Sustainability".

In the IS, the core of the activities entail some divergence mechanisms between economic capital and environmental or natural benefits, like the fact that the volume of by-products produced and consumed in the network evolves mostly aside from the price incentives as evidenced in the further chapters composing this study. The main insight related to strong sustainability is that by-products are not commodities in the strict sense; their production relies on the production capacity of the main product, and this avoids in principle the substitutability between human capital and natural capital. They cannot be seen as commodities, because their economic viability depends on the reduction of production costs due to the position of the by-product, in respect to the central production process. If the by-product turns into main product, then the cost composition changes and it becomes economically non-viable. Therefore, an increase in the demand for a by-product needs an underpinning increase in the main product demand, otherwise the IS's demand is not supplied and uncertainty rises in the symbiosis. Furthermore, one of the main reason of IS's limited emergence worldwide is the risk in by-products regular supply, which depends on the firms' main production volumes (Aurez & Georgeault, 2016)

METHODOLOGY

The foreseen methodology has led to the emergence of two underpinning approaches: the qualitative and quantitative. The quantitative approach is embodied by the industrial metabolism (material and energy flow analysis), economic cost-benefit analysis (eco-efficiency aims and resilience indexes); the qualitative approach seeks to match the quantitative through the implementation of system dynamics in a geographical proximity approach. The geographical SD approach utilized in this research gave us the flexibility to integrate quantitative and qualitative data based in data collected from the literature review and semi-directive interviews to the stakeholders.

The previously mentioned approach supply the overall research with three main strengths in comparison with the other methods existing in the literature. First, the approach allows the identification of complex dependence relationships alongside with the biophysical exchanges accountancy in the industrial network. Based on the recognition of complexity in social industrial ecosystems, it emerges as a tool to cope with complex adaptive changes in the system, with the ability to produce better long-term scenarios. Second, the geographic economy axe provides explanatory mechanisms for social qualitative analysis, thus IS is recognized as the most evolved experience of territorial cooperation (Yazan, Romano, & Albino, 2016) where stakeholders, encompasses a profitable arena to get a better understanding of social industrial ecosystems. Finally, we use ecosystem theory as a mechanism to approach the system's complexity through the analysis of positive and negative behavioural patterns, a structural analysis that provides a systemic answer to the way actors influence the ecosystem's dynamic.

It is important to provide theoretical foundations for a methodology, which, from the best of our knowledge, has not been used in the analysis of IS, encompassing biophysical and economic quantitative data together with qualitative social information in a structure explicative model. The theoretical foundations help to give clarity to the arguments supporting this methodological choice. The geographical system dynamics method tries to integrate the differences while identifying the common features, to ensure their ability to represent territorial mental models, thus one of the main contributions of CLDs is the identification of key drivers able to cause large-scale changes in the system from small adjustments, a kind of multiplier effect. Even when parallel visions coexist in the understanding of the industrial ecosystem, the coincidences' identification could contribute to draw up agreements and collective trajectories; therefore, geographic system analysis gives access to structural and long-term simulations of the public policy interventions.

Multidimensional and interdisciplinary studies need to be engaged, assuming eco-efficiency (that quantitatively accounts energy and material), resilience (component referring to diversity and ubiquity of activities and network actors); and the normative governance aspects (focused on social proximity and cooperation implementation) as encompassing drivers for sustainable IS implementation. Finally, we foresee to discuss the obtained symbiotic models in a systemic perspective and with an interdisciplinary approach, which is essential to entail management (cooperation mechanisms, supply chain management, network logic, etc.); economics (spatial economy, economies of scale, local development, etc.) and social sciences (which leads to the improvement of organizational aspect embedded in cultural changes associated with economic behavior).

Altogether, environmental and economic indexes will be proposed to assess IS (Felicio, Amaral, Esposto, & Gabarrell Durany, 2016) in a dynamic perspective. To achieve this goal, it is necessary to state the eco-efficiency, resilience, proximity and cooperation boundaries within the strong sustainability understanding. The literature review on IE and SD help to address the research work to interdisciplinary customers and stakeholders associated with the occurrence and functioning of symbiosis. SD is a methodology that can power or accelerate behavioral changes by incorporating, removing, or altering the structural mechanisms of stakeholders' influence. With the publication of the books Industrial Dynamics (Forrester, 1961), Urban Dynamics (Forrester, 1970) and Limits to growth (Meadows, Meadows, Randers,

& Behrens III , 1972), a tradition starting point in the use of SD to approach complex models management.

For the case studies, we used data from publicly available sources, interviews, site visits, and collaborations with local organizations. Public available sources consist of reports published by governmental environment agencies in France and Mexico. We then cross validate the public available data obtained from the document analysis presented by interviewing some practitioners and stakeholders representatives of the symbiosis network.

We present the dilemma between eco-efficiency maximization and the resilience quest, as the narrative string conducting the analysis of IS all the long of this dissertation. After introduction, chapter one enables a literature review analysis and figure out some indicators and assessment tools in a multidimensional perspective; those tools are necessary to interweave the IS strategy within a geographical proximity, without disregarding the interdisciplinary and systemic complexity.

In the study, I provide a critical outlook of the IS, encompassing on the one hand relative eco-efficiency related to the industrial metabolism evaluation, considering material, energy and monetary flows in an environmental and economic dimension. On the other hand, the IS's resilience, outlining the firm diversity and waste ubiquity as IS variables, and then analysed using the impact index to the disruptive events consisting in firm removal. We describe current resilience, eco-efficiency, proximity, autonomy and commitment, cooperation and competition of the symbiotic network to understand the endurance of relationship in the industrial production.

The CLD used in this study as part of the qualitative analysis of IS in the chapter 7 enables the description of all the key drivers in the industrial ecosystem entailing feedback cycles. For this, it is necessary to analyze the system within a geographical proximity perspective encompassing the interconnected feedbacks loops and evaluating its behavior as part of a holistic system. The feedback loops unfold causal relationships between stakeholders and resources displayed in the CLD, feeding the system with the existing environmental conditions, and recognizing this information as a flow that in turn influences future decision-making. We often think about one-directional flows, but system thinking introduces the concept of feedback loops. SD as methodological tool paves the way to encompass the systems thinking in the industrial ecosystem. Even when the output of those calculations seems to be obvious, and the reinforcing and balancing loops are predefined by the way we measure them, the novelty in this analysis is to engage the necessary means for the dynamic and systemic analysis in the IS, in regards to the four cross connections of this sustainable strategy.

Chapter 1 goes deeper in the theoretical framework, analyzing the epistemological difference between strong and weak sustainability and the practical implications on the selected conceptual choice for the sake of political and strategic program proposed. We start from a set of assumptions aiming to define the boundaries of strong sustainability. We present here the strong sustainability differences and similarities in order to support the four theoretical pillars applied in the IS governance. The strong sustainability principles are based on the balance seeking insight, looking for the viability window on the social sphere of industrial ecosystem. The four axes are relationship (cooperation/competition), scale (local/global), circular viability (efficiency/resilience) and governance (democracy/leadership). This conceptual framework (Diemer & Morales, 2017), is presented in the paper[7] entitled "Can industrial and territorial ecology trigger a strong sustainability model in the developing countries? Illustration by the Tampico industrial symbiosis case study in Mexico" and will be further developed at the literature review section.

Chapter 2 stands out what is known today about this social innovation strategy of inter-firm cooperation. The strong sustainability principles of IS are based on concurrent dialectic values triggering the four axes across the socio ecological dimension: the relationship (cooperation/competition), the scale (local/global), the circular viability (efficiency/resilience) and the governance (Bottom-up/Top-down). Symbiosis state of art includes an international article presented in the Journal of Sustainability (2019) Servitization in Support of Sustainable Cities: What Are Steel's Contributions and Challenges?

Chapter 3 begins with a critical point of view on the IE methodological analysis, concerning the IS study in the scientific literature, establishing a typology of different methodological research examples in the field of industrial ecosystem synergies. Critical review of existing

[7] This scientific paper is in French language and the original title is "L'écologie industrielle et territoriale peut-elle s'affirmer comme un véritable modèle de développement durable pour les pays du Sud? Illustration par le cas de la symbiose industrielle de Tampico au Mexique?

methodological tools, presented in the chapter 11 of the book *Europe and Sustainable Development: Challenges and Prospects (2017) with the title "Analyzing Symbiotic Relationships in Sustainable Cities - A framework".*

Chapter 4 entails a set of hypotheses to frame the boundaries of the strong sustainability model. This model is based on a methodology supported by two global approaches: the quantitative component: industrial metabolism (Chertow & Erhenfeld, 2012) (Fraccascia, Giannoccaro, & Albino, 2017); and the quantitative approach of SNA represented by a grid of surveys among the various stakeholders of a symbiosis (Boutillier, Laperche, & Uzunidis, 2015). The representation of the industrial system through an early CLD let us accomplish a better understanding of the industrial ecosystem dynamic (Forrester J. , 1961) (Forrester J. W., 1969) (Lane D. , 2008) (Sterman J. , 2000). The assumptions proposed all along the dissertation is presented in that chapter: *Who gets the benefits from an industrial and urban symbiosis? An embeddedness analysis in a sustainable city ecosystem.* Published in the book *European Cities, the road to Sustainability (2018),* the referred assumptions are:

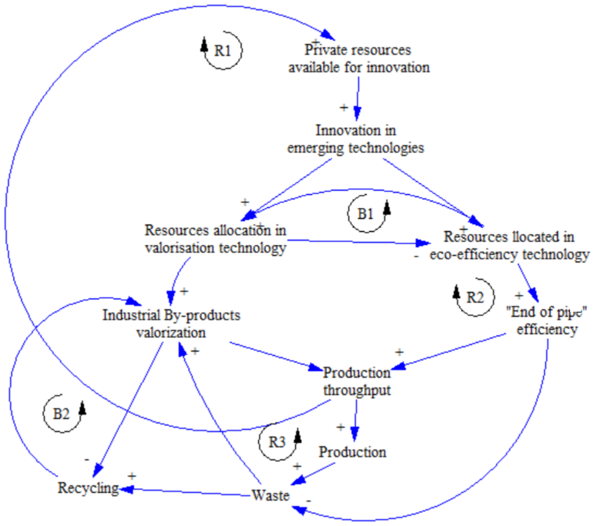
a. Industrial ecology approaches are essentially interdisciplinary,
b. The economic evaluation of industrial ecology approach still be favored over other important criteria such as resilience, cooperation and proximity,
c. Social and organizational factors are at the heart of IE,
d. ITE is an embedded territorial approach,
e. The existence of inadequate assessment methods for social parameters, according to the IS environment.

Chapter 5 is devoted to the IS historical development pathway in Altamira, Mexico, developed in the document: "By-products synergy" changes in the IS dynamics at the Altamira-Tampico industrial corridor: 20 years of industrial ecology in Mexico published in the Journal of Resources, Conservation & Recycling 140 (2019) 235-245. The case of Altamira deserves some attention, referring one of the first IS experiences in Latin-America (Duret, 2007), located in the Altamira petrochemical corridor leaded by the WBCSD-Gulf of Mexico. Subsequently, this experience becomes as a model for many other experiments in the US and Canada. The Altamira IS case study entails a strong sustainability method, coming from a territorial proximity approach, the relevance of this study bet on the fact that its applied strategies could be reproduce in the industrial ecosystem elsewhere, if their local context allows them to attempt to gather the territorial conditions to implement it in developing countries. It presents the industrial symbiosis as a social innovation decentralized strategy encouraging cooperation, in the sought of balancing trade-off policies, considering the systemic feedbacks and their delays in the long term, accomplished between the different stakeholders in the territory.

Chapter 6 embraces the territorial context of Altamira through eco-efficiency and resilience outlook, presented in the paper *"Industrial symbiosis' innovative approach based on circularity, concurrent resilience and efficiency"* accepted for publication at the Journal of Industrial Ecology (2019). The paper serves to clarify the territorial context through the eco-efficiency and resilience of Altamira's IS. We figure out how strong and positive sustainability apply a methodological pathway to assess the efficiency and resilience. As well as the proposed motivations identified in the IS in the sought for sustainability.

Chapter 7 includes the Dunkirk case study, which is the perfect example of a sustainable industrial port transition turning the techno-economic trajectory since the 1980s, with a central motivation in the battle against pollution and unemployment, through significant environmental efforts, among which, IE is well represented (Boutillier, Laperche, & Uzunidis, 2015). This chapter develops a geographical approach supported across the SD analysis of Dunkirk, contributing to a better social understanding of the IS's strategies regarding the stakeholder's relationship and motivations role. The integration of geographical proximity approach without disregarding the diversity of assessment tools for the social dimension (economic, ecological, political and cultural), which provides a better understanding of the overall behavioral patterns in the industry.

Figure 6. Interlinks between "end of pipe" efficiency and the Dunkirk governance system



In the Figure 6, we have identified three positive loops that reinforce the dynamics of the industrial system in Altamira and Dunkirk, standing out the main connection between Chapter 6 and 7. 1) When "Private resources available for innovation" is low in the system, the "Innovation in emerging technologies" are also low, which hampers the "Resources allocation in valorization technology", reducing at the same time the "Industrial By-products valorization", which at the end produce a negative impact in the "Production throughput". Therefore, reinforcing the feedback loop of low "Private resources available for innovation". 2) When "Private resources available for innovation" are low in the system, the "Innovation in emerging technologies" are also low, which hampers the "Resources located in eco-efficiency technology", reducing at the same time the "End of pipe – efficiency" implementation, which at the end produces a negative impact in the "Production throughput"; closing the reinforcing feedback to the "Private resources available for innovation".

We follow our analysis with the third reinforcing loop where 3) the larger the "Industrial By-products valorization", the higher the "Production throughput", therefore influencing the "Production" volume, which at the same time provoke an increase in the "Waste" volume. The increase in "Waste" encompasses an increase in the "Industrial By-products valorization", closing the reinforcing feedback of the system.

Two balancing loops where identified in the industrial ecosystem of IS, the first one regards the sharing of investments between "Resources allocated in eco-efficiency" and the "Resources allocated to "Industrial By-products valorization", as they are limited the more we invest in eco-efficiency the less is provided to "Industrial by-products valorization. The second identified balancing loop is the relationship between "Recycling" and "Industrial By-products valorization", the higher the "Recycling" share in the industrial ecosystem the lower by-products available to develop "Industrial by-product valorization" in consequence.

NEW INSIGHTS PROPOSED FOR INDUSTRIAL SYMBIOSIS

Given the importance, understanding the sustainability of IS has to be the new imperative of IE research, and for this reason is relevant to give further impetus to circular viability processes, to reduce dependency on raw materials, and to encourage optimal resources use and recycling (UN-DESA, 2018). Driving the firm into a low vulnerability status where the impact of disruption has a low risk probability could reduce the lack of resilience and paving the way to a IS, achieving long-term endurance on its structure and systems.

SUSTAINABLE ECOSYSTEMS IN THE QUEST OF RESILIENCE AND EFFICIENCY COOPERATION

Ecosystems can be understood from a business perspective, identifying the existence of opposite poles and their trade-off to find a balance in industrial ecosystems such as standardization/diversity, control/autonomy, efficiency/resilience, cooperation/competition, individual/collective, among others (Diemer & Morales, 2016). An essential contribution to the industrial systems understanding is the implementation of dynamic analysis of networks, considering actors' diversity subject to contradictory values and interests. The previous network analysis cannot be conceived in a static way, since the network is always changing and it aims to integrate the mechanisms of dynamic change into the transitional drivers and identify the behavioral patterns that can contribute in the pursuit of positive sustainability[8] (James, 2015).

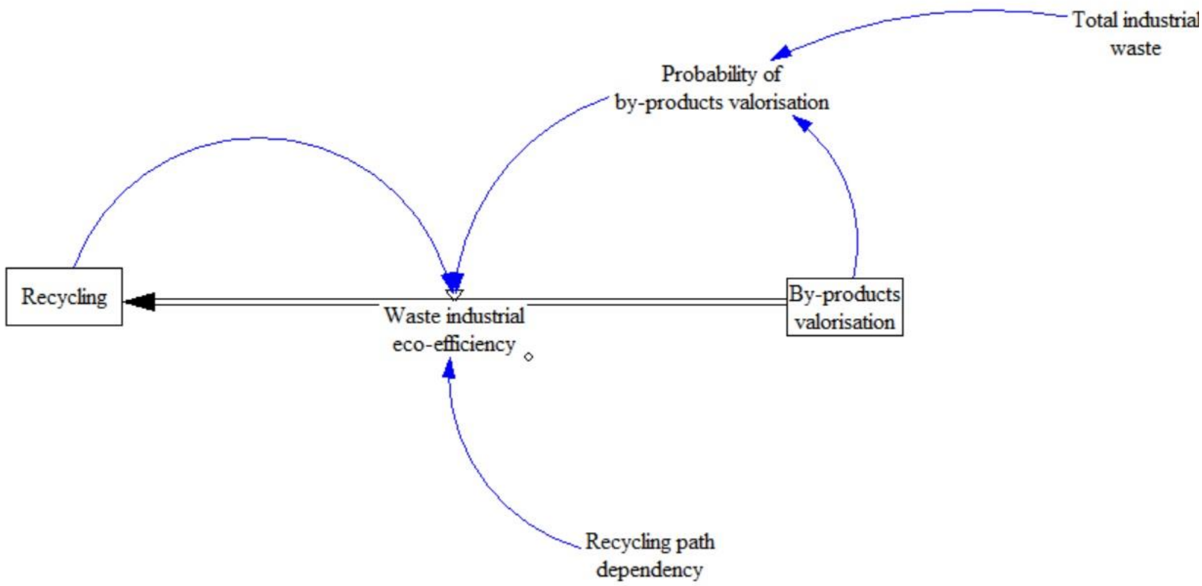
[8] Positive sustainability are all those practices and commitments that are engaged voluntary and that give us the possibility to think about future scenarios that would promote wellbeing in the long term, including the natural and social dimension to basic conditions of life.

Efficiency

In the context of this research, efficiency of IS is understood as the average measure of individual production efficiency gains related to the IS existence. The concept of technical efficiency at IS is especially interesting, when showing the capacity of the organization to transform input into output, engaged in the cost minimization. In this sense, efficiency is expressed by the relationship between the product and its inputs, measured in physical units of output compared against the physical units of inputs, regarding cost minimization (Valderrama, Neme, & Ríos, 2015).

The eco-efficiency concept is embedded in the efficiency understanding and according to the WBCSD means more value with less impact (Verfaille & Bidwell, 2000). It aggregates the essential components to enhance the economic and environmental performance through a more efficient utilization of production resources, generating at the same time lower emissions to the environment and reliable monitoring tools for managers, shareholders and stakeholders. Industrial eco-efficiency regarding the waste treatment can be measured by a relationship between economy and ecology, expressed in the following systemic diagram.

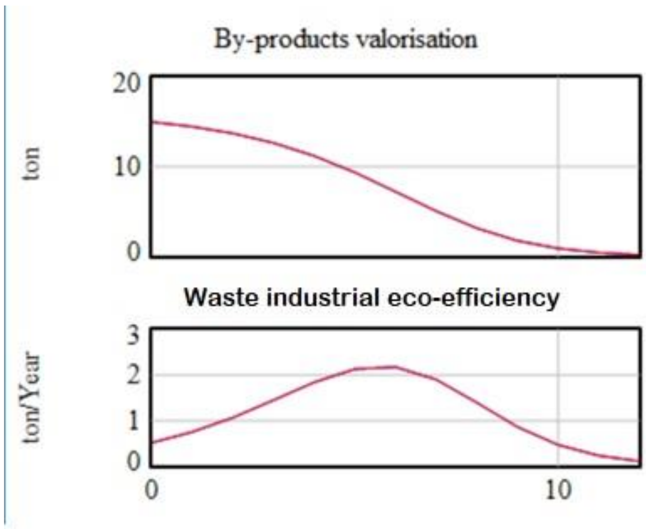
Figure 7. Eco-efficiency calculation



The Figure 7, illustrate the fact that there is a relationship between Industrial waste eco-efficiency and the available waste to be send to the Recycling or the By-products valorization activities. There is a balancing loop also represented between Recycling and By-products valorization. The more waste is diverted to recycling facilities; the less by-products are available in the local territory to be valorized and reintegrated into the local production cycles. There is also an identified path dependency, described in Chapter 5, that impact the By-product valorization potential in the IS, coming from the Recycling inertia.

The research about efficiency in waste management is used as an insight in our analysis, considering the balance between cost and efficiency of environmental actions. Moreover, the economic implications of the pollution thresholds depend on the phenomenon of marginal efficiency of green investments. This observation is related to decreasing returns in economy, because beyond cyclical variations, expenditure continues to increase and the progress in depollution has less relative efficiency as showed in the Chapter 6, with the data gathered from the Altamira BPS.

Figure 8. Eco-efficiency behavioral pattern in the Industrial waste management in Altamira BPS, and the impact in the By-products valorization

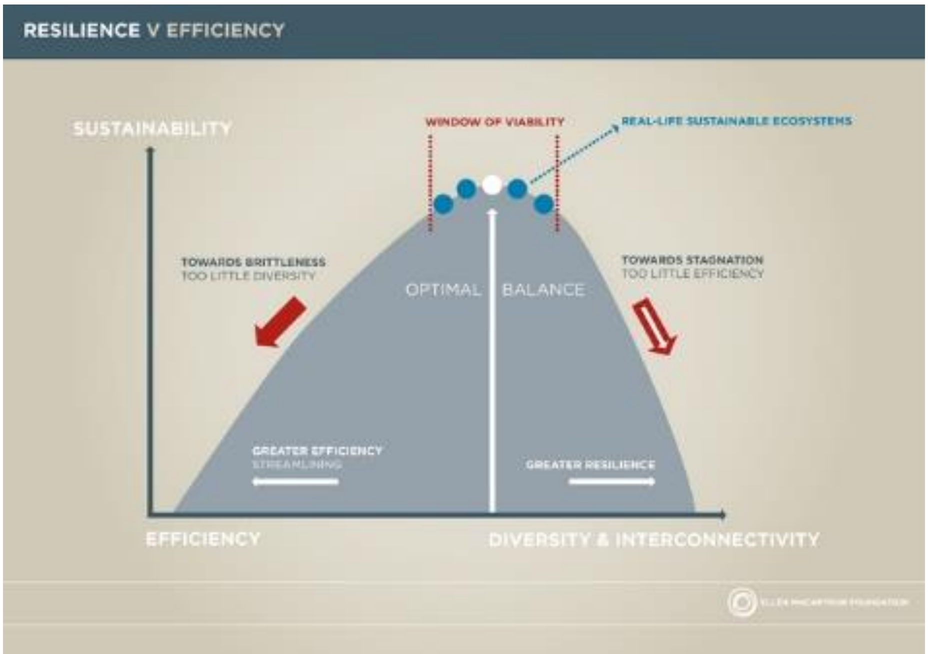


The negative efficiency spill-over effects are correlated with the lack of resilience in the industrial ecosystem, avoiding the resilience trade off in the long term that will assure the sustainability of environmental investments, evading the marginal throughputs; accomplishing risky and uncertain behavior for stakeholders, when disregarding the resilience of the system. To determine the best indicators for industrial ecosystem (Verfaille & Bidwell, 2000) one suggestion is the use of economic parameters: 1) the net turnover of goods or services delivered to clients, and 2) the cost of inputs (supplies and raw materials) necessary for the industrial processes. In addition, for the environmental dimension they recommend: 1) energy requirements, 2) material entrance and disposal, 3) water input and disposal, and 4) GHG emissions.

The IS eco-efficiency goal is the substitution of primary inputs by wastes of other production processes where there will be no waste to dispose of and no primary input to purchase from external suppliers. Once the IS is structured within the network (Yazan, Romano, & Albino, 2016), this is understood under the environmental (material and energy) and economical (monetary efficiency) point of view. Both frameworks (economic and environmental) are relevant to achieve eco-efficiency; therefore, cooperation between actors became crucial (Vanalle, Moreira, & Lucato, 2014). The productive efficiency determines the system's ability to maximize throughput in the short-term, and the resilience allows for divergent processes in the IS, maintaining a degree of freedom. When resilience and efficiency are developed altogether, the outcome is a more sustainable industrial ecosystem, embedded in a dynamic outlook coming from resilience and settled down in the industrial ecosystem.

In the IS, firms depend on each other waste to function. If they want to grow, assuming that most firms have an incentive to grow, then they would like to have more input, meaning more waste from other firms. However, if those firms are trying to maximize efficiency at the firm's level (micro-efficiency), then this reduces the amount of waste they produce – and then the possibility for growth to other firms that depend on those waste for production. For example, In the Altamira IS, the firm CABOT depends on the INSA's wastewater, so if CABOT wants to maximize this, while firm INSA wants to minimize it, because it makes it individually more monetarily efficient. Thus, we will find a global contradiction because what seems to be a benefit under a micro-efficiency regard, ends on a middle–out approach (Costa & Ferrão, 2010) disadvantage, which also has negative side effects to INSA firm and the other firms of the network. Therefore, cooperation in the IS present a physical limit for the individual efficiency, subject to a greater collective benefit on the industrial network, called network resilience.

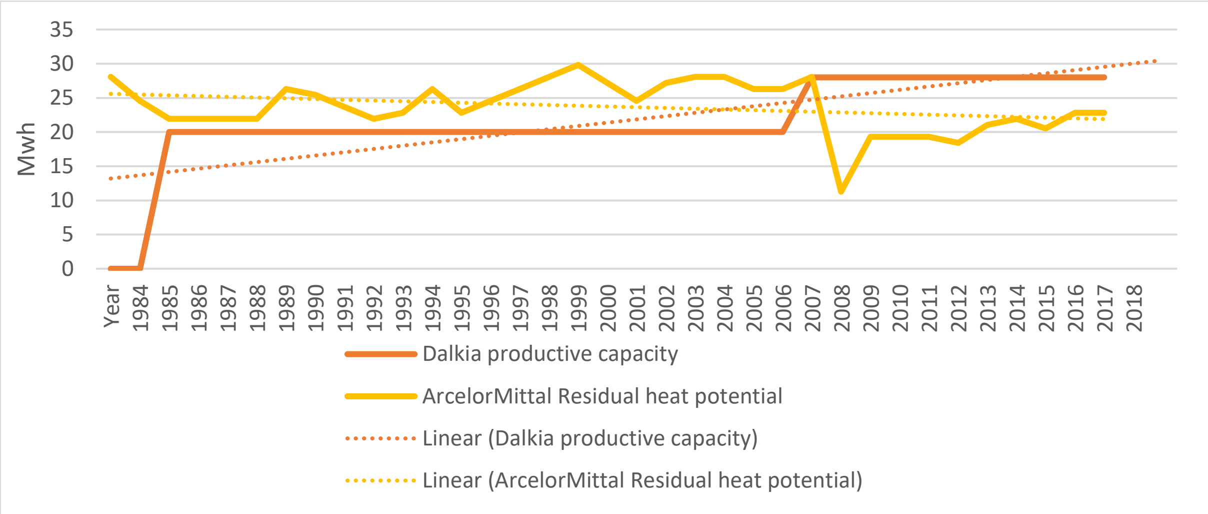
Figure 9. The window of viability in the Industrial Symbiosis -Resilience Vs Efficiency



Source: Goerner, Sally, & Voller, Randolph. (2013). Rebuilding Economic Vitality — R.E.V. (Ellen MacArthur Foundation, 2013)

In the IS, the firms' location is determined by other conditions more than the location of by-product suppliers, because by definition, the by-products production firms are multifunctional. Multifunctional firms accomplish functions other than by-product exchange, which plays an ancillary role. Therefore, the by-product exchange perspective does not influence *a priori* their location in the territory, establishing a geographical proximity interrelationship between production and consumption, which is different from mono-functional production firms. In the multi-functional firms the BPS depends on primary production processes, unfolding a direct relationship where the greater the final production, the more by-products are generated. Thus, a feedback loop is identified in the production side, since the higher the efficiency in reducing waste, the lower the amount of by-products available to be shared. The synergy between the companies Dalkia and Arcelor Mittal, embedded in the Dunkirk industrial Symbiosis illustrate very well the feedback loop between waste reduction and by-products stock decrease. Through the graph depicted in the Figure 10 (further developed in chapter seven), we can infer that the greater the amount of by-product available for manufacture, the higher the amount of production desired by Dalkia. Therefore, the larger the required installed capacity in the long term, influencing simultaneously the real production through previous commitments concerning the returns over investment of the project. Systems analysis applied to Dalkia-Arcelor's industrial synergy; let us assume that an increase in efficiency of steel process tends to reduce the available stock of by-products in the territory.

Figure 10. Comparison between Dalkia's production capacity and the current and future supply potential of Arcelor-Mittal steelmaking steam



In addition, another balancing loop highlighted in the Figure 6 triggers international price volatility regarding scarce minerals, those minerals been essential for the steel industrial production, unfold a decrease on the production supply, and consequently in the available stock of by-products dependent on steel production. When the residual heat (Arcelor Mittal's by product) became more and more scarce for Dalkia, the production price increase because Dalkia was forced to import natural gas to supply the residual heat scarcity in the symbiosis in order to keep electric power production at full capacity.

Key drivers have been identified in the IS, as mechanisms that steer the transition to a strong sustainability in the industry. First, the internal production assessment looking for the viability window in the intersection between reduction costs resulting from efficiency (Boiral, 2005)) and the by-products industrial synergies, resulting in industrial resilience. Thus, up to a certain threshold, the investment in "end of pipe" technology became more expensive than the attended economic and social benefits; and resetting the potential benefits of by-products in industry is highly attractive. Therefore, the by-products previously considered as unworthy acquire value, internalizing the amortization of the investment cost in efficiency.

Another key driver analysed is the waste management implications, which is often dismissed in the analysis of negative and positive externalities. The cost of waste management is usually high, due to high specialization required, rules and regulations imposed that firms should internalize. However, when implementing BPS, instead of spending in waste reduction, management and transport, the fees disappear because the waste is transformed and sold as by-product. The decision between investing in eco-efficiency at the production process and shifting towards by-products generally depends on every firm's features and environment, in addition with the managerial and organizational skills of stakeholders.

Resilience

Resilience was introduced to the ecological literature by (Holling, 1973), who stated, "Resilience determines the persistency of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and still persist". The feature of resilience emerges during the transition of an ecosystem between two equilibrium states. When the first equilibrium state is lost due to a perturbation, the system has to react in order to regain an equilibrium state (Holling, 1996). Two schools of knowledge frame the concept of resilience with a different regard, the first sustains that the ecosystem returns to its initial equilibrium state after the perturbation. Accordingly, resilience of an ecosystem is defined as "how fast the variables return towards their equilibrium following a perturbation" (Pimm, 1984). Hence, this definition refers to a static conceptualization of resilience. The second school recognizes that the ecosystems are complex systems able to evolve over the time. Hence, rather than return to its state before the perturbation, such a system may evolve towards a new equilibrium state different from the previous one (Gunderson, 2000). In accordance with this point of view, resilience could be defined as "the capability of a system to absorb disruption[9] and reorganize it while undergoing change so as to keep essentially the same structure, function, drivers and flows". This definition refers to a systemic conceptualization of resilience, drawn from the concept of ecological resilience.

[9] A disruptive event is defined as any event able to affect the feasibility conditions of IS relationship, altering the current equilibrium state of the ISN from a technical, economic, and/or normative point(s) of view (Garner & Keoleian, 1995)

Two alternative measures are used to assess resilience depending respectively on the two schools of thought previously quoted. Accordingly, to the former, resilience is measured as the degree to which the system has moved away from the equilibrium state (in time) and how quickly it returns (Ludwing, Walker, & Holling, 1997). According to the latter, resilience is measured by the magnitude of disturbance that a system can absorb before redefining its structure by changing the variables and processes that control behavior (Holling, 1973). The definition of resilience used in this study is the capability of a system to absorb disruption[10] and reorganize it while keeping essentially the same structure, function, drivers and flows. This definition refers to a systemic conceptualization of resilience, drawn from the concept of ecological resilience, setting off in this study.

We understand the IS as an ecosystem where the firms correspond to the organism and perform specific functions. These functions correspond to the waste exchanges among firms. In doing so, the IS generates two main services: i) to create economic benefits for firms (organisms); and ii) to create environmental benefits for the network as a whole (external environment). The systemic resilience depends on their structural features, in particular those of diversity and redundancy. Two kinds of diversity have been distinguished in the literature and associated with resilience: *functional-group diversity* and *functional-response diversity* (Walker, et al., 2006). A functional group is defined as a group of different organisms with the same functions (for instance pollination, predation or decomposition); referring to the amount of functions performed within the system by the organisms that compose it. However, even within the same functional group, the different organisms can reply differently to environmental changes, the higher the number of different responses, the greater the functional response diversity of the system. Both diversities (number of *different functions* performed within the system and the number of *different responses* to environmental changes) are given to play a relevant role in fostering resilience in ecosystems.

Redundancy refers to the number of species that perform the same function. If a specie with a strong ecological function is removed, the consequences for the system may be of greater

[10] A disruptive event is defined as any event able to affect the feasibility conditions of IS relationship, altering its current equilibrium state from a technical, economic, and/or normative point(s) of view (Garner & Keoleian, 1995)

importance than if a species with minor ecological impacts is removed (Walker B. , 1992). Therefore, in order to guarantee high resilience, it is vital that high redundancy is guaranteed especially for key functions. Recent studies framing IS as CAS (Chertow & Ehrenfeld, 2012) have also contributed to drive research towards the investigation of IS resilience, since it is presented here as one of the main pillars explaining the sustainability of such systems. Resilience is a typical feature of CAS, i.e. systems made of interconnecting agents who self-organized and emerge into coherent forms without any entity controlling this process (Holland, 2006). Two different conceptualizations of complex systems resilience are recognized in the IS: i) the outcome-based and the process-based. This approach considers resilience in terms of the outcome: accordingly, the system is more resilient when the propensity of positive or neutral outcome following a disruptive event is high; a system able to achieve a "bounce back" outcome after a disruptive event is more resilient than other systems whose outcome after the same disruption is "recovery but worse than before" or "collapse".

In this sense, resilience depends on the adaptive capacity of such systems, since this feature is related to the capacity to provide answer to changes (Smit & Wandel, 2006). On the other hand, the process-based conceptualization focuses on the ability of systems to absorb events, using predetermined coping responses (Cutter, et al., 2008). This is known as the absorptive capacity of the system. The greater the absorptive capacity of the system, the higher its resilience will be. Overarching resilient complex system is characterized by high levels of adaptive and absorptive capacity, fostered by innovation and learning capabilities.

Resilience of engineering systems is defined as the *"ability of a system to identify, recognize, adapt and absorb variations, changes, disturbances, disruptions and surprises"* (Hollnagel, Woods, & Leveson, 2007). Therefore, resilience of engineering systems has been investigated with reference to a static conceptualization, coherently with the first school of thought of ecological studies on resilience. Two different types of disruptions are distinguished: external and systemic ones (Madni & Jackson, 2009). The first category includes events not depending on the functioning of its components, such as natural disaster, whereas the second includes losses in function, capability or capacity of more components that drew up the system. Network theory is the preferred approach to assess resilience of engineering systems. Each component of the system composes the model as a node and links among nodes simulate the physical connections. Disruption affecting one element of the system displays the unavailability of the correspondent node. System resilience enables the ability of the network to function when nodes disappear or became unavailable. As evidenced in (Fraccascia, Giannoccaro, & Albino, 2017; Santos & Magrini, 2018), the most critical nodes are the most connected ones. Furthermore, networks with low redundancy in connections are more vulnerable to disruptive events.

Some previous literature concerning the resilience analysis limitations, let us bring some insights into the systemic analysis and figure out a resilience impact index (Fraccascia, Giannoccaro, & Albino, 2017), coherent with the theoretical framework. Firm removal is one of the most critical disruptions able to distress the IS, however other less dangerous but more frequently disruptive events can also occur; events such as changes in the production levels, equipment failures and operation mistakes, which trigger a partial disruption.

The system's ability to maximize throughput depends on streamlining processes that are adapted to a given context (internal order, increasing external entropy). Their resilience on the other hand depends on their capacity to allow for divergent processes, maintaining a degree of freedom that diminishes efficiency but increases resilience. The sustainability concerning the circular viability axe in the IS could be understood through efficiency and resilience balance in the respect of biophysical limits. We need to avoid large collapses and this requires governance (encompassing proximity and cooperation) which means maintaining the right balance between freedom (resilience) and order (efficiency).

Concepts and framework from different disciplines are borrowed; when relevant to the better understanding and application of resilience and efficiency to productive IS systems: 1) IE as a discipline reproduces in the industry the principles of natural ecosystems (Frosh, 1992). 2) The complex systems literature, because IS are approached as CASs (Chertow & Ehrenfeld, 2012) and resilience is one of the main properties of CASs. Finally 3) Engineering systems since IS relationships are implemented within a network of firms, aiming the co-location of material/energy/information exchanging networks to work better (Lowe, 1997).

Firms' sustainability expects to be improved when embedded in an IS, mainly because they act on the self-regulating balance of the industrial ecosystem; with the resilience cutting down the dangerous over efficiency individual ambition, regulated by the collaborative input-output exchange. Sustainability at IS should be analyzed on an interdisciplinary basis, with data from the real environmental and economic benefits resulting from eco-efficiency use of resources and the underpinning resilience impact. IS can bring sustainability to companies (in a quantitative approach) if they retrieve the resilience to the sustainability equation, internalizing diversity (actors and activities) and redundancy as relevant drivers to sought for sustainability. Firms with the higher eco-efficiency demonstrate the lowest rate of resilience in the IS, thus we can conclude that the strategies that strive only for eco-efficiency on the IS have a negative impact on the overarching system's resilience. Therefore, we assume that the sustainability will decline in the long term, as we can appreciate in the Altamira BPS case study, fully developed in the Chapter 6.

SECTION I - THEORETICAL FOUNDATIONS

CHAPTER 1. FIELDS OF STUDY AND GENERAL THEORIES

L'écologie industrielle et territoriale peut-elle s'affirmer comme un véritable modèle de développement durable pour les pays du Sud ? Illustration par le cas de la symbiose industrielle de Tampico au Mexique[11]

Could Industrial and territorial ecology become a strong sustainable model for developing countries? Depicting Tampico By-product case study in Mexico

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ABSTRACT

Industrial and territorial ecology (ITE) as a field of study has been analyzed only in developed countries, when it could be presented a strategy in the sought of strong sustainability even in developing countries. The ITE ground theories and foundations are not opposite to the industrial perspectives at developing countries. We highlight IS as a strategy embedded in the ITE, in the pursuit of environmental, economic and social benefits to companies involved in a collaborative relationship. Depicting the interdependence between firms' production processes and the energy and material flows exchange indeed a territorial industrial ecosystem, paving the way towards a strong model of sustainability in terms of socio-economic development.

Keywords

Cooperation, Industrial Ecosystem, Resilience, Symbiosis, Tampico

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[11] Ce texte s'inscrit dans un travail de recherche associé au programme Franco-mexicain (CONACYT) et au programme européen Marie Curie - ADAPTECON II. Cette recherche vise à proposer une méthodologie (la dynamique des systèmes) pour appréhender les symbioses industrielles, trois études de cas sont proposées : Kalundborg (Danemark), Dunkerque (France) et Tampico (Mexique). Nous remercions les deux rapporteurs anonymes pour leurs remarques et commentaires

RESUME

Le champ de l'écologie industrielle et territoriale, longtemps associé aux expériences menées dans les pays développés, ouvre de nouvelles perspectives d'industrialisation pour les pays du Sud. Nous insistons plus précisément sur une forme particulière d'écologie industrielle et territoriale (EIT), la symbiose industrielle. Les symbioses industrielles sont porteuses de bénéfices environnementaux, économiques et sociaux pour les entreprises impliquées dans une relation de collaboration Selon nous, elles illustrent d'une part, la nécessaire interdépendance entre plusieurs processus de production de différentes firmes et le bouclage des flux d'énergie et de matière à mettre en œuvre à l'intérieur d'une zone d'activité industrielle territorialisée et d'autre part, l'avènement d'un modèle de durabilité forte en termes de développement socioéconomique.

Mots clés

Coopération, Développement industriel, Résilience, Symbiose, Tampico

INTRODUCTION

Il est généralement admis que l'acte fondateur de l'écologie industrielle revient à deux employés de General Motors, Robert Frosch, vice-président de la recherche et Nicholas Gallopoulos (1989), responsable de la recherche sur les moteurs (Erkman, 1997). Tous deux ont émis l'idée selon laquelle il était nécessaire de passer d'une économie linéaire où les ressources sont extraites d'un écosystème, exploitées par des activités humaines et renvoyés à l'écosystème sous forme dégradée, à une économie circulaire puisant de façon marginale dans le stock de ressources naturelles, recyclant les biens usagés et limitant les déchets (Dannequin, Diemer, Petit, Vivien, 2000). Les stratégies menant à cette transition, prirent ainsi quatre directions : la valorisation des déchets sous la forme de ressources ; le bouclage des cycles de matière et la minimisation des émissions dissipatives ; la dématérialisation des produits et des activités économiques ; la décarbonisation de l'énergie. Les sciences de l'ingénieur, les sciences économiques et sociales, les sciences de gestion furent ainsi mobilisées pour établir une étude de faisabilité et analyser les facteurs de pérennité de l'écosystème industriel ainsi créé (Diemer, Labrune, 2007).

Par la suite, les géographes se sont emparés de l'objet « écologie industrielle » afin de lui donner une dimension territoriale (Buclet, 2011). La recherche de synergies entre acteurs fût présentée comme un des moyens de réduire l'impact des activités humaines sur l'écosystème. Cette recherche de synergies présupposait des formes de coopération entre entreprises et collectivités territoriales, notamment au niveau de territoires au périmètre non déterminable. L'intérêt de l'écologie industrielle porta ainsi sur la création d'interactions entre acteurs relativement proches géographiquement, mais n'ayant pas toujours l'occasion d'échanger, faute d'intérêts communs (Diemer, 2013). Le champ de l'écologie industrielle et territoriale était ainsi définie, et avec lui, l'importance dévolue aux acteurs territoriaux (collectivités locales) et aux flux d'interactions (écologie urbaine et métabolisme).

Dans le papier que nous proposons, nous suggérons de partir du modèle d'écologie industrielle et territoriale, non pas pour en tirer les quelques enseignements issus des expériences menées dans les pays développés et industrialisés, mais pour en faire une réelle opportunité en matière de développement des pays du Sud. Nous insisterons plus précisément sur une forme particulière d'écologie industrielle et territoriale (EIT), la symbiose industrielle. Chertow a défini la symbiose industrielle comme " *engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*" (2004, p. 2; 2007, p. 12). Les symbioses industrielles sont porteuses de bénéfices environnementaux, économiques et sociaux pour les entreprises impliquées dans une relation de collaboration (Brullot, Junqua, 2015; Brullot, Buclet, 2011). Selon nous, elles illustrent d'une part, la nécessaire interdépendance entre plusieurs processus de production de différentes firmes et le bouclage des flux d'énergie et de matière à mettre en œuvre à l'intérieur d'une zone d'activité industrielle territorialisée (Diemer, 2015, 2016), et d'autre part, l'avènement d'un modèle de durabilité forte en termes de développement socioéconomique. Afin d'étayer cette thèse, notre article sera structuré en deux parties.

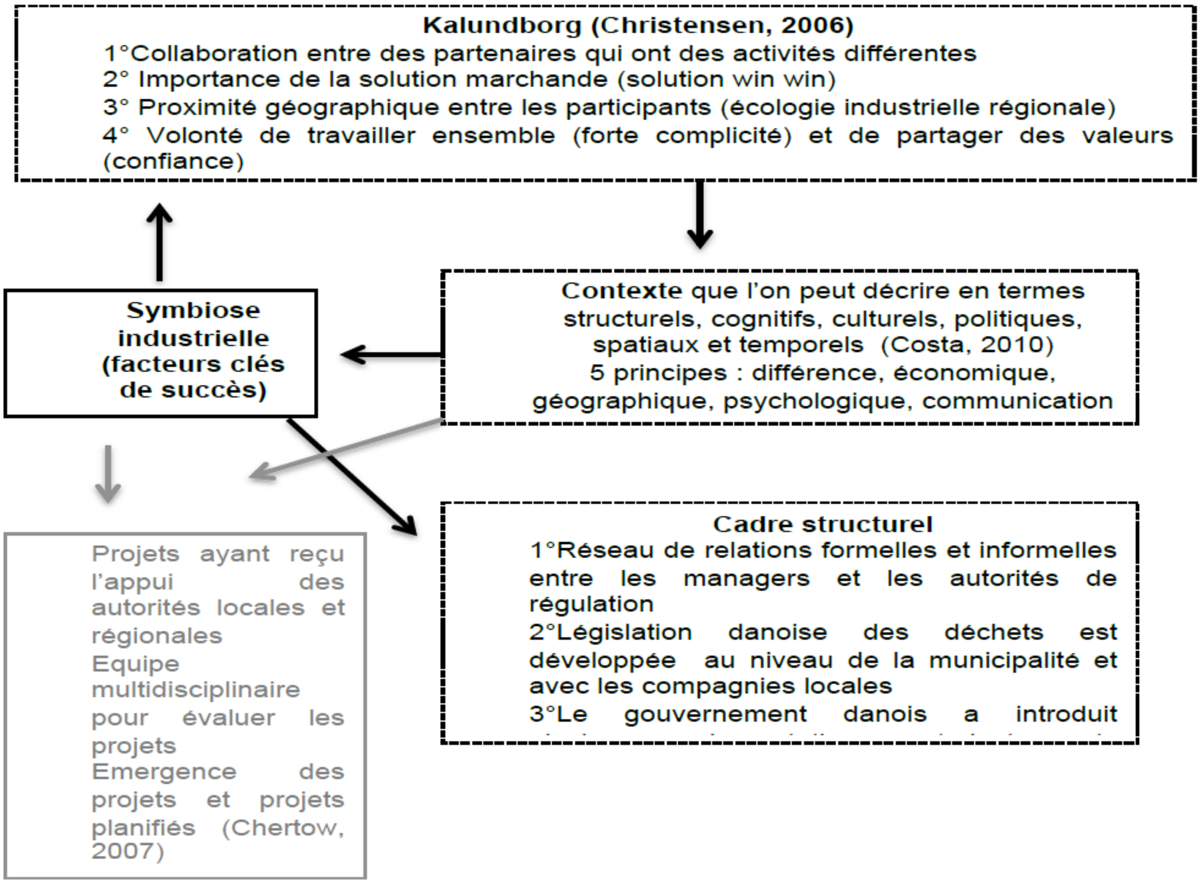
La première partie s'attachera à présenter le cadre méthodologique de l'étude d'une symbiose. Il s'agit de partir d'un ensemble d'hypothèses visant à délimiter les contours d'un modèle de durabilité forte. La durabilité forte entend limiter la croissance économique et l'usage de la technique à ce que le milieu biophysique est capable d'assimiler. Elle renvoie au courant de pensée d'économie écologique « *Ecological Economics* », dont les racines sont profondément ancrées dans la bio-économie de Nicholas Georgescu Roegen (1971, 1978, 1979) et le concept de *Steady State* de Herman Daly (1977, 1991). Les origines du paradigme Bioéconomique de Georgescu-Roegen se situent au carrefour de la vision thermodynamique du monde présentée par Sadi Carnot et des travaux du biologiste Alfred Lotka (Dannequin, Diemer, 1998): « *La thermodynamique et la biologie sont les flambeaux indispensables pour éclairer le processus économique et découvrir ainsi ses propres articulations, la thermodynamique parce qu'elle nous démontre que les ressources naturelles s'épuisent irrévocablement, la Biologie parce qu'elle nous révèle la vraie nature du processus économique* » (1978, p. 353). De son côté, Herman Daly définit the Steady State Economy comme « *an economy with constant stocks of people and artifacts, maintained at some desired, sufficient levels by low rates of maintenance "throughput", that is, by the lowest feasible flows of matter and energy from the first stage of production to the last stage of consumption* » (1991, p. 17). Il s'agit d'une part, de revenir aux limites biophysiques et écologiques de la planète (ressources naturelles, populations humaines…) et d'autre part, de prôner une stabilité du stock de capital naturel (le capital naturel et le capital artificiel seraient ainsi deux facteurs complémentaires et non substituables de la fonction de production). Au début des années 90 (après l'institutionnalisation de l'ISEE – *International Society for Ecological Economics* – en 1988 et le lancement de la revue *Ecological Economics* en 1989), le courant de pensée d'économie écologique se présentait ainsi comme une volonté d'établir des relations entre les écosystèmes et les systèmes économiques (Constanza, 1989). Les activités humaines pouvaient être décrites en termes de flux d'énergie et de matière, les systèmes écologiques pouvaient intégrer des questions économiques (Ropke, 2005). Si le courant de pensée *Ecological Economics* trouve ses fondements dans une approche de la durabilité forte, nous pensons qu'il est possible d'étendre ces perspectives à l'écologie industrielle et territoriale, et plus précisément aux symbioses industrielles. Le modèle de durabilité forte que nous entendons présenter ici, s'appuie sur quatre piliers : *l'éco-efficacité* associée au métabolisme industriel, *la collaboration* apposée aux relations marchandes, *la proximité* comme principe de synergie territoriale et la *résilience* comme la capacité de la symbiose à résister aux chocs externes et internes.

La deuxième partie sera consacrée à l'étude de la symbiose de Tampico au Mexique. Si le mythe de la symbiose de Kalundborg continue à alimenter les débats (Chertow, Ehrenfeld, 2012), le cas Tampico mérite qu'on s'y attarde quelque peu (Macchiavelli, 2008). C'est en effet l'une des premières expérimentations d'écologie industrielle (Duret, 2007). Elle a été initiée sur la zone industrielle de Tampico par la branche régionale du WBCSD (Gulf of Mexico). Par la suite, ce projet a servi de modèle à de nombreuses autres expériences aux Etats Unis et au Canada. La symbiose industrielle de Tampico prendrait ainsi les traits d'un modèle de durabilité forte, ancré sur un territoire et donc, propice au développement local (et non national). Son succès pourrait « *tordre le coup* » aux politiques de libéralisation de l'économie préconisées par les grandes institutions internationales afin d'assurer le développement économique des pays du Sud. La symbiose serait en quelque sorte une forme de coopération (économique) décentralisée, dans laquelle les relations entre les différents acteurs d'un territoire s'appuient sur les synergies potentielles.

LA SYMBIOSE INDUSTRIELLE, UN MODELE DE DURABILITE FORTE

Il existe une importante littérature sur les symbioses industrielles (Chertow, 2007, Zhu, Lowe, Wei, Barnes, 2007), si la plupart des travaux ont focalisé leur attention sur le modèle de Kalundborg (Domenech, Davies, 2010), certains ont cherché à définir les facteurs clés de cette *success story* (Buclet, 2011 ; Diemer, Figuière et Pradel, 2013). Cinq facteurs seraient à l'origine du succès de Kalundborg: (i) la collaboration entre des participants opérant sur des secteurs d'activité différents, (ii) l'importance de la solution marchande, (iii) une proximité géographique entre les participants (écologie industrielle régionale; (iv) la volonté de travailler ensemble et de partager des valeurs, (v) la bonne communication entre les partenaires. Plus récemment, Diemer (2013, 2016, 2017) est revenu sur ce qu'il appelle les cinq principes susceptibles de produire une symbiose industrielle, à savoir le *principe de différence*, le *principe économique*, le *principe géographique*, le *principe psychologique* et le *principe de communication*.

Figure 11. Les facteurs de succès de la symbiose industrielle de Kalundborg



Source: Diemer (2013, pag. 145)

Dans ce qui suit, nous souhaiterions focaliser notre attention sur ce que nous appellerons les quatre postulats de la durabilité forte d'une symbiose.

Le premier ces postulats, ***l'éco-efficacité***, renvoie aux travaux sur le *métabolisme industriel*, cher aux ingénieurs (Esquissaud, 1990). Il s'agit plus précisément de mesurer quantitativement et qualitativement la dimension physique des activités économiques, à savoir les flux et les stocks de matières et d'énergies inhérents à toute activité industrielle (Ayres 1989). Dans un ouvrage intitulé *Changer de Cap :* Réconcilier le développement de l'entreprise et la protection de l'environnement[12], Stephan Schmidheiny et le WBCSD associaient la méthodologie du métabolisme industriel au *principe d'éco-efficience*. Selon Erkman, cette méthodologie consiste « *à établir des bilans de masse, à estimer les flux et les stocks de matière, à retracer leurs itinéraires et leur*

[12] Cet ouvrage, qui n'est en fait qu'un rapport, a été présenté au sommet de la Terre (Rio, 1992).

dynamique complexes, mais également à préciser leur état physique et chimique » (Erkman, 1998, p. 56).

Au sein même des entreprises, cette comptabilisation est réalisée sous la forme d'une matrice input-output et d'une analyse du cycle de vie (ACV). Ces « bilans environnementaux » permettent de contrôler les échanges, de connaître le niveau auquel ils se produisent, de savoir comment ils se structurent et comment ils déstructurent l'environnement. D'un point de vue économique, le métabolisme industriel comprend tous les flux de matière et d'énergie qui permettent au système économique de fonctionner, c'est-à-dire de produire et de consommer (Hertwich, 2005). Il permet ainsi de changer notre perception de la valeur d'un bien (généralement associée à la loi de l'offre et la demande, au prix du marché) en incluant des facteurs écologiques, sociaux et culturels via des flux de matières, d'énergies et d'informations (Passet, 1991). La seule zone d'ombre au tableau est de remettre la société entre les mains de l'ingénieur, le seul susceptible d'intégrer toutes les contraintes systémiques : « *Engineers are accustomed to contending with a variety of design constraints, from the most rigid thermodynamic laws to budgetary constraints to issues of social justice. Ecological constraints add one more set of considerations to the list. Engineering designs are now expected to result in products and managment plans who use or implementations will not endanger important ecological conditions and processes* » (Schulze, Frosch, Risser, 1996, p. 1).

Dans ce qui suit, nous insisterons davantage sur la notion ***d'éco-efficacité*** que sur celle d'éco-efficience. Ce choix est justifié par trois raisons : (i) centrer l'analyse sur l'objectif à atteindre et non sur la minimisation des coûts, (ii) déconnecter les flux physiques des flux monétaires de manière à partir d'une comptabilité biophysique (exemple des *Physical Input-Ouput Tables, PIOT*), (iii) replacer les solutions dans un cadre systémique et non simplement technologique.

Le deuxième postulat stipule que si la symbiose industrielle s'inscrit dans *une logique marchande* (création de valeur), elle ne fait pas de la concurrence, une condition d'efficacité. Bien au contraire, les relations marchandes au sein de la symbiose s'appuient sur des synergies entre les acteurs qui préfèrent privilégier ***la collaboration*** à la compétition. Dans un précédent papier (Diemer, Morales, 2016), nous avions insisté sur le principe de coopération. La collaboration permet d'insister sur la longévité des relations au sein d'un écosystème (dans les relations interentreprises, la coopération peut être associée à une phase de répit dans le processus concurrentiel ou alors à une stratégie de minimisation des coûts ou encore de conquête de parts de marché). Elle implique également l'idée de co-construction (c'est l'acte de réfléchir ou de travailler ensemble pour atteindre un objectif, elle s'appuie ainsi sur le principe d'éco-efficacité) et l'utilisation d'outils collaboratifs (réseau social, partage de savoirs et de connaissances, communication…).

L'écosystème industriel doit ainsi s'inspirer des nombreuses relations entre les êtres vivants présentes dans l'écosystème naturel (*relation d'indifférence* avec le neutralisme et la synécie ; *relation antagonique* avec la compétition, la concurrence, l'amensalisme, la prédation et le parasitisme ; *relations favorables* avec le commensalisme, la synergie, l'aide mutuelle, la coopération et la symbiose). La durabilité « forte » de la symbiose renvoie ainsi à un *changement de paradigme*, un basculement de l'économie concurrentielle vers l'économie collaborative (Vallat, 2015). La première est un modèle économique basé sur l'échange, la valeur prix et une logique d'optimisation en termes de biens, de services, de temps et de connaissances entre les acteurs. La seconde consiste à concevoir et à produire des solutions intégrant des biens et des services selon deux types de dynamique: (i) le passage de la vente de biens et de services à une véritable réflexion sur les valeurs d'usage; (ii) une approche systémique permettant de prendre en compte toutes les externalités (environnementales, sociales, politiques…).

Notons que si l'économie collaborative est étroitement liée à l'économie sociale et solidaire (Defalvard, 2016), ses fondements trouvent dans l'écologie industrielle et territoriale, un terrain fertile pour les expériences de symbioses industrielles dans les pays du Sud. En effet, la collaboration peut emprunter les voies de la coopération décentralisée (Berr, Diemer, 2016). Elle peut prendre la forme d'une mutualisation de moyens du point de vue économique, d'un partage ou d'un don sous l'angle social, d'une meilleure gestion des ressources naturelles et énergétiques du point de vue environnemental… Au niveau de la symbiose, l'économie collaborative présente un certain nombre d'avantages (Terrasse, 2016): (i) les consommateurs sont également des producteurs ; (ii) la participation intervient à toutes les étapes du procès; (iii) la relocalisation permet de générer de nouvelles synergies ; (iv) la dématérialisation peut établir un pont avec l'économie de la fonctionnalité (importance de la valeur d'usage) ; (v) la mutualisation (propriété collective) peut venir compléter la propriété individuelle…

Table 4. Les relations au sein d'un écosystème

Relations d'indifférence	*Relations antagoniques*	*Relations favorables*
Le neutralisme : absence de toute trace d'association ou d'antagonisme entre des espèces qui coexistent dans un même milieu. *La synécie* : c'est le cas de deux partenaires régulièrement associés sans que l'un soit pour l'autre source d'avantages ou d'inconvénients.	*La compétition* : il s'agit d'une lutte pour des ressources limitées. *L'amensalisme* : certains êtres vivants utilisent des substances toxiques pour lutter contre leurs rivales. *La prédation* : c'est l'utilisation d'un être vivant par un autre être vivant pour s'en nourrir. *Le parasitisme* : c'est l'utilisation d'un être vivant par un autre être vivant pour se nourrir ou se reproduire sans engendrer fatalement sa mort.	*Le commensalisme* : c'est une association qui ne profite qu'à l'un des deux êtres vivants associés, lequel vit difficilement ou ne peut vivre, hors de la présence de l'autre à qui il est indifférent. *La synergie* : c'est la stimulation de l'activité ou du développement d'un être vivant par la présence d'un autre. *L'aide mutuelle* (ou coopération) permet à de nombreux êtres vivants de s'associer entre eux pour en tirer un bénéfice réciproque. *La symbiose* est la forme la plus évoluée d'association entre des êtres vivants car les protagonistes y bénéficient d'avantages réciproques et ne pourraient pas subsister, ou alors très mal, hors de cette union.
Dans un écosystème industriel, il peut s'agir de firmes qui se côtoient sans se porter grande attention (activités différentes). C'est le cas d'entreprises présentes dans une zone industrielle ou commerciale.	Dans un écosystème industriel, la compétition est liée au nombre de firmes, elle sera d'autant plus intense que ces dernières sont sur les mêmes marchés ou exercent la même activité. Des stratégies d'absorption, de scission et des OPA (offres publiques d'achat) hostiles peuvent prendre forme.	Dans un écosystème, le commensalisme s'apparente à une relation de sous-traitance. La vie du sous-traitant dépend du bon vouloir du donneur d'ordre. Les incubateurs et les clusters sont symptomatiques des relations synergiques. Les partenariats d'entreprises, les coopératives et les créations de filiales communes s'inscrivent dans une démarche coopérative et collaborative. La symbiose est l'idéal type du processus associatif. La mise en commun de ressources, de savoirs, de capitaux… et de compétences permet à la symbiose. Les firmes peuvent être si imbriquées qu'elles constituent une nouvelle entité.

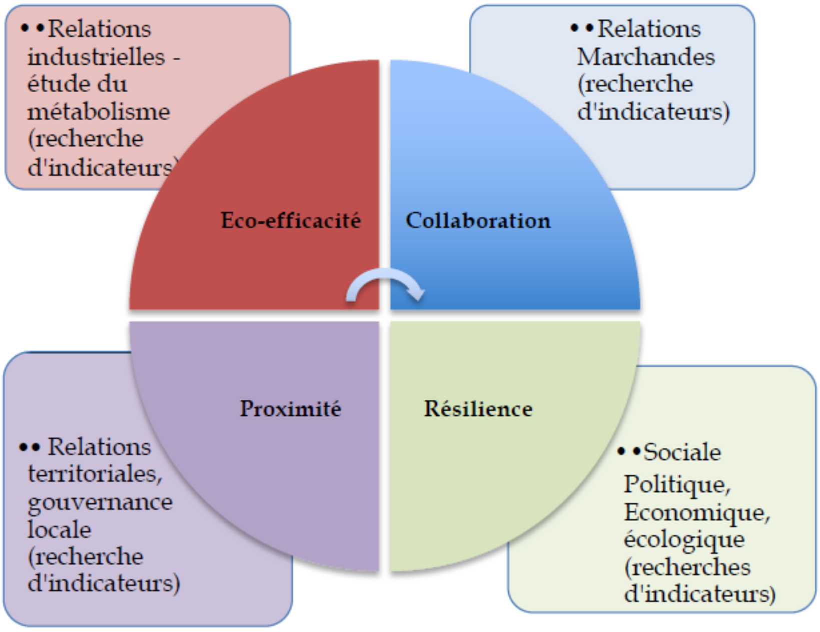
Le troisième postulat stipule qu'une symbiose industrielle repose sur des *relations territorialisées***.** Le territoire peut être perçu comme un espace fonctionnel permettant de traduire des enjeux locaux (retraitement des déchets, assainissement de l'eau, dépollution de sites industriels…) et introduisant un principe clé, le ***principe de proximité*** (il s'agit à la fois d'une distance *spatiale* – coût de transport –, *psychologique* – qualité du produit et subjectivité dans les relations - et communicationnelle – outils collaboratifs, lieux informels ou formels de discussions et de rencontres). Le territoire insiste sur la capacité des acteurs à proposer de nouvelles formes de collaboration qui, non seulement, peuvent engendrer des résultats économiques, environnementaux et sociaux positifs, mais peuvent également et surtout contribuer à la résurgence de l'intérêt collectif entre acteurs inscrits dans un même territoire (mise en place de schémas de cohérence territoriale ou d'agendas 21). D'une certaine manière, les symbioses industrielles trouvent dans l'écologie territoriale, un terreau susceptible de promouvoir une certaine idée de la durabilité. Selon Nicolas Buclet (2015, p. 16), l'écologie territoriale trouve ses racines dans l'écologie urbaine (Wolman, 1965 ; Odum, 1976) et l'écologie industrielle (Billen et al, 1983). Deux approches qui ont fondé leur analyse sur la méthodologie du métabolisme (établir et mesurer les flux entrants et sortants) et sur la question de la gouvernance locale. Cette dernière est associée à l'ensemble des mesures, des règles, des organes de décision, de surveillance et d'information qui permettent d'assurer le bon fonctionnement d'une organisation (ici la symbiose) et une communication transparente vis à vis des *parties prenantes* (Freeman, 1994, Dosse, 1995). D'un point de vue opérationnel, l'étude de la gouvernance locale suppose (i) d'identifier les différents mécanismes et systèmes qui coexistent (entreprises capitalistes, associations, coopératives, collectivités publiques…) ; (ii) de comprendre leur mode de fonctionnement et d'évaluer les effets de leurs politiques en matière de durabilité (environnementale, sociale, culturelle, économique) ; puis de s'interroger sur les différents scénarii possibles en matière de coopération (répartition et partage des pouvoirs au sein d'une symbiose).

Le quatrième et dernier postulat, ***la résilience***, suppose que la symbiose industrielle s'inscrive dans un système *d'interactions socio-écologiques et socio-politiques*. Holling (1996) a distingué deux définitions de la résilience (Martin, 2005). La première renvoie à la stabilité proche de l'équilibre, la résistance à la perturbation et le temps mis par un système pour retourner dans le voisinage de l'équilibre sont utilisés pour mesurer la propriété de résilience (Pimm, 1984). La résilience rime ainsi avec équilibre et stabilité, elle est liée principalement aux systèmes linéaires. Holling (1996, p. 33) parle « *d'engineering résilience* ». La seconde définition met en évidence les conditions loin de tout équilibre où des instabilités peuvent faire passer le système vers un autre régime de comportement, c'est-à-dire dans un autre domaine de stabilité (Holling, 1973). La résilience est mesurée par l'intensité maximale des perturbations que le système peut absorber sans changer de structure, de comportement ou de processus de régulation. Holling parle de « *ecological resilience* ».

Dans la suite de cet article, nous ne retiendrons que cette dernière définition. La résilience suppose que l'on analyse la tension maximale qu'une symbiose peut supporter sans changer son système de fonctionnement ou sa structure organisationnelle. Ainsi, une interaction entre les propriétés de stabilité et d'instabilité est au cœur de la résilience et plus largement du développement durable. La disparition d'un acteur important, la perte d'un client, la mise aux normes environnementales des installations… sont autant de facteurs susceptibles de déstabiliser la symbiose. Plus généralement, la résilience doit être analysée sous plusieurs angles. Il s'agit tout d'abord de souligner le rôle joué par les pouvoirs publics, que ce soit l'Etat, les conseils régionaux ou les collectivités territoriales. L'autorité publique est à la fois (i) une force de propositions (cadre opérationnel pour la dépollution des sites industriels, financement de pipelines pour les échanges de flux d'énergie et de matière) ; (ii) un garant de certaines valeurs (justice, tolérance, respect d'autrui…) ou encore (iii) un animateur territorial (l'acteur public doit savoir mobiliser, susciter la participation, créer l'innovation sociale …). Il s'agit ensuite de comprendre comment la symbiose communique avec l'extérieur (création d'un Institut de la Symbiose, destiné à analyser les succès de ce modèle) et en son sein (communication formelle et informelle, place des conventions et de la confiance dans les relations humaines). Il s'agit enfin de mieux concevoir les interactions avec la société, c'est-à-dire de cerner les dimensions sociales (création d'emplois, dispositifs de réinsertion sociale…) et politiques (information des citoyens, processus de vulgarisation, notes d'informations, participation aux prises de décisions). Ainsi, les modèles de symbiose industrielle ne s'inscriront dans une démarche de durabilité forte qu'à la condition de susciter une véritable acceptabilité sociale (débats citoyens, culture de la concertation, projet éducatif…).

Ces quatre postulats (éco-efficacité, collaboration, proximité et résilience) renvoient directement aux interactions qui se développent au sein d'une symbiose et permettent de positionner cette dernière dans un cadre de durabilité forte.

Figure 12. Les quatre postulats de la durabilité d'une symbiose



LA SYMBIOSE DE TAMPICO, UNE ILLUSTRATION D'UN MODELE D'ECOLOGIE INDUSTRIELLE ET TERRITORIALE AU MEXIQUE

L'écologie industrielle n'est pas un luxe réservé aux pays riches. On peut avancer au moins trois arguments principaux conduisant à penser que l'écologie industrielle devrait être considérée comme une stratégie pertinente et prioritaire pour les pays du Sud:

- La mondialisation de l'économie rend anecdotique toute tentative de transformation confinée aux pays riches, alors que ces derniers ont déjà transféré dans des pays du Sud une bonne partie de leur activité industrielle (surtout celles nécessitant beaucoup de matières premières et d'énergie) ;
- La majeure partie de la population mondiale se trouve dans les pays du Sud, et son poids démographique va encore s'accroître. De plus, le pouvoir d'achat de cette population augmente en moyenne, et surtout, son style de vie devient de plus en plus consumériste. Les problèmes des déchets et des ressources se posent donc de manière encore plus aiguë dans ces pays ;
- La trajectoire d'industrialisation des pays du Sud diffère profondément de celle des pays riches. En Europe et aux Etats-Unis, le processus d'industrialisation s'est fait progressivement, laissant tant bien que mal la possibilité de corriger a posteriori les

> problèmes principaux. Les pays actuellement en voie d'industrialisation et d'intégration dans l'économie globalisée connaissent un processus beaucoup plus rapide. Il en découle que les approches préventives, telle que l'écologie industrielle et territoriale, deviennent des priorités urgentes, alors que le traitement traditionnel des déchets selon la philosophie end of pipe apparaît comme un luxe peu efficace.

Etant issue à l'origine, aux Etats-Unis et en Europe, de quelques cercles d'ingénieurs et de responsables d'entreprise, l'écologie industrielle a pu donner l'impression de ne concerner que les pays industrialisés. Mais il n'a pas échappé à un certain nombre de pays, notamment en Asie, que le concept d'économie circulaire appliqué à l'écologie industrielle et territoriale était non seulement l'une des meilleures stratégies pour modérer les impacts négatifs de l'industrialisation, mais aussi un atout non négligeable pour accroitre la compétitivité de leurs économies (Erkman, 1997).

Histoire de l'écologie industrielle au Mexique

Alors que l'écologie industrielle a connu un essor rapide dès le début des années quatre-vingt-dix aux Etats-Unis, au Canada, au Japon et en Europe du Nord (Diemer, 2017), l'intérêt pour ce nouveau champ de recherches, au Mexique, s'est d'abord caractérisé par une assez longue période de latence. Toutefois, cette latence semble devoir diminuer rapidement, compte tenu de l'attention croissante que rencontre actuellement l'écologie industrielle dans divers milieux économiques, politiques et administratifs du pays. Mis à part les travaux précurseurs du *"Business Council For Sustainable Development"* et du *"South Tamaulipas Industrial Association"* sur le site de Tampico (1997), force est de constater que l'intérêt pour l'écologie industrielle est resté marginal au Mexique jusqu'au début du XXIème siècle. Le premier colloque éco-industrielle fût organisé à l'Institut Polytechnique National (IPN) en 2006, à l'initiative de Gemma Cervantes Torre-Marín.

En 2007, le Groupe de Recherche en Ecologie Industrielle (GIEI en espagnol) – en partenariat avec l'Unité Professionnelle Interdisciplinaire en Biotechnologie de l'IPN et avec le soutien du Conseil National de la Science et la Technologie (CONACYT) – a développé quelques projets d'écologie industrielle relatifs aux agrosystèmes (Xochimancas, District Fédéral et Tochtli entre 2008 et 2009). Cette période coïncide avec la collaboration du groupe de Recherche AGSEO de l'Université Autonome Métropolitaine (2008). L'AGSEO héberge la première chaire doctorale d'écologie industrielle au Mexique (2006), via la réalisation de la thèse doctorale de la professeure Graciela Carrillo à l'Université de Barcelone. Depuis 2008, l'AGSEO propose une étude de cas du Parc Industriel Altamira-Tampico et du Parc Industriel Toluca 2000, qui malheureusement fermera ses portes l'année suivante, suite à des problèmes organisationnels. En 2011, le GIEI a développé des projets d'écologie industrielle dans la gestion des déchets solides urbains dans la Vallée du Mexique. En 2012, un projet de biocarburants associé aux algues marines a vu le jour sur le site d'Altamira-Tampico.

En ce qui concerne la gestion environnementale des zones d'activités pour la valorisation et la mutualisation des ressources entre entreprises, le Réseau Mexicain d'écologie industrielle, sous l'impulsion du GIEI et notamment de Gemma Cervantes Torre-Marín, a favorisé dès 2010 la mise en œuvre de pratiques relevant de l'écologie industrielle dans les zones d'activité des Institutions membres: Université Autonome de Querétaro, Université de Guanajuato, Université Technologique de León, Université Autonome Métropolitaine et l'Institute Polytechnique National.

Parmi tous les projets d'écologie industrielle, il existe un champ de recherches et d'actions opérationnelles qui focalise l'attention des décideurs politiques. C'est la recherche de synergies entre acteurs, qui est présentée comme un des moyens de réduire l'impact des activités humaines sur l'écosystème (Buclet, 2011). Cette recherche de synergies présuppose des formes de coopération entre entreprises et collectivités territoriales, notamment au niveau de territoires au périmètre non déterminable. L'intérêt de l'écologie industrielle serait ainsi de créer des interactions entre acteurs relativement proches géographiquement, mais n'ayant pas toujours l'occasion d'échanger, faute d'intérêts communs (Diemer, 2013). Le champ de l'écologie industrielle et territoriale était ainsi définie, et avec lui, l'importance dévolue aux pouvoirs publics (collectivités locales) et aux synergies entre les différents acteurs.

Table 5. Expériences de Parcs Industriels au Mexique

Code	Dates	Projet	Porteur du projet	Périmètre	Pour aller plus loin
1	1997-Aujourd'hui	*«By Productsinergy»*	*"Business Council for Sustainable Development"* et *"South Tamaulipas Industrial Association"*	*Corredor Industriel Tampico-Altamira*	http://oldwww.wbcsd.org/DocRoot/VvYTNmsJuZwcZxjtYQJ3/USBCSDBPSfullcasefinal.pdf, http://148.206.107.15/biblioteca_digital/capitulos/423-5762uki.pdf
2	2010	Bouclage de flux	The Brownsville Economic Development Council (BEDC)	Corredor Industrial Matamoros-Bronsville	http://www.inge,nieroambiental.com/7/manual03.pdf
3	2007-2009	*Industrial Symbiosis Programme (NISP)*	Etat du Mexico gouvernement et l'Ambassade du Royaume Unis	Etat du Mexico	http://www.cmic.org/comisiones/sectoriales/medioambiente/Varios/Descargas_en_PDF/Concentrado%20sobre%20NISP%20Septiembre%202009.pdf, http://148.206.107.15/biblioteca_digital/capitulos/423-5768ozr.pdf,
4	2013	*Micro Parc Eco-Industrielle*	Université Autonome de l'état du Mexico en coopération avec le gouvernement de l'Etat du Mexico.	Tepeji del Río	http://www.uaeh.edu.mx/investigacion/productos/5570/3_micro_parque.pdf

En reprenant le cadre de l'écologie industrielle et territoriale défini précédemment, nous présenterons l'expérience mexicaine de la symbiose industrielle de Tampico, qui est l'une des premières expérimentations d'écologie industrielle dans les pays du Sud (Duret, 2007). Ce projet a été initié sur la zone industrielle de Tampico par la branche régionale du WBCSD. Par la suite, ce projet a servi de modèle à de nombreuses autres expériences aux Etats Unis et au Canada.

La symbiose industrielle TAMPICO, le modèle "By-product Synergy"

Le projet de symbiose industrielle a été portée par le WBCSD – Gulf of Mexico. Il a vu le jour en 1997 dans la ville de Tampico, Etat de Tamaulipas. Tampico est l'un des ports les plus actifs du Mexique et le site industriel de la région de Tampico-Altamira se prêtait particulièrement bien à une initiative de recherche de synergies de sous-produits (*By-products synergy*) :

- Les activités du site étaient liées aux secteurs de la chimie et de la pétrochimie dont les procédés de fabrication génèrent souvent des sous-produits réutilisables,
- La proximité des entreprises devait faciliter les échanges,

- La plupart des entreprises étaient membres d'une association locale d'industriels qui avaient déjà l'habitude de travailler ensemble,
- Enfin, 18 des 21 industries impliquées dans le projet étaient certifiées ISO 9000 et ISO 14000.

Tous ces aspects ont constitué des conditions favorables au lancement de ce projet. Il s'agissait tout simplement de mettre en place une dynamique visant à systématiser les échanges de matières et d'énergie sur le site existant. Les motivations qui ont mobilisé les acteurs autour de ce projet, sont multiples : diminution des consommations énergétiques, réduction de l'impact environnemental de l'activité industrielle, opportunités en termes d'échanges, réduction des émissions de gaz à effet de serre (par la réduction de la demande en matériaux bruts et de la mise en décharge).

L'étude préalable d'identification des synergies potentielles s'est étalée entre octobre 1997 et janvier 1999. Les différentes phases du projet (prise de conscience – collecte des données - analyse et mise en oeuvre - évaluation) ont permis de répertorier 373 flux de matières (199 entrants et 174 sortants) et d'identifier une douzaine de synergies potentielles.

Etape de prise de conscience et collecte de données

Parmi l'ensemble des synergies répertoriées, seules trois d'entre elles ont été mises en place dont une partiellement. Les autres n'ont pas pu aboutir pour des raisons de rentabilité économique, de contraintes réglementaires ou techniques, d'éloignement géographique, ou encore suite à un manque de réactivité ou de confiance. D'une manière générale, 21 entreprises de la zone industrielle de Tampico, parmi lesquelles on trouve 18 membres de l'Association d'Industrielle du Sud de Tamaulipas A.C. (AISTAC), présentent une réelle responsabilité individuelle et collective vis-à-vis de l'environnement et du développement durable et continuent d'être attentives aux opportunités d'optimisation de leurs ressources comme l'eau ou l'énergie. Elles communiquent bien entre elles, notamment grâce à l'association qui les rassemble, ce qui leur permet d'entretenir un bon niveau de confiance et d'échanger des bonnes pratiques. L'action de coordination et de lobby auprès du gouvernement mexicain du bureau local du BCSD facilite grandement la réflexion et la mise en œuvre des principes de l'écologie industrielle à Tampico[13].

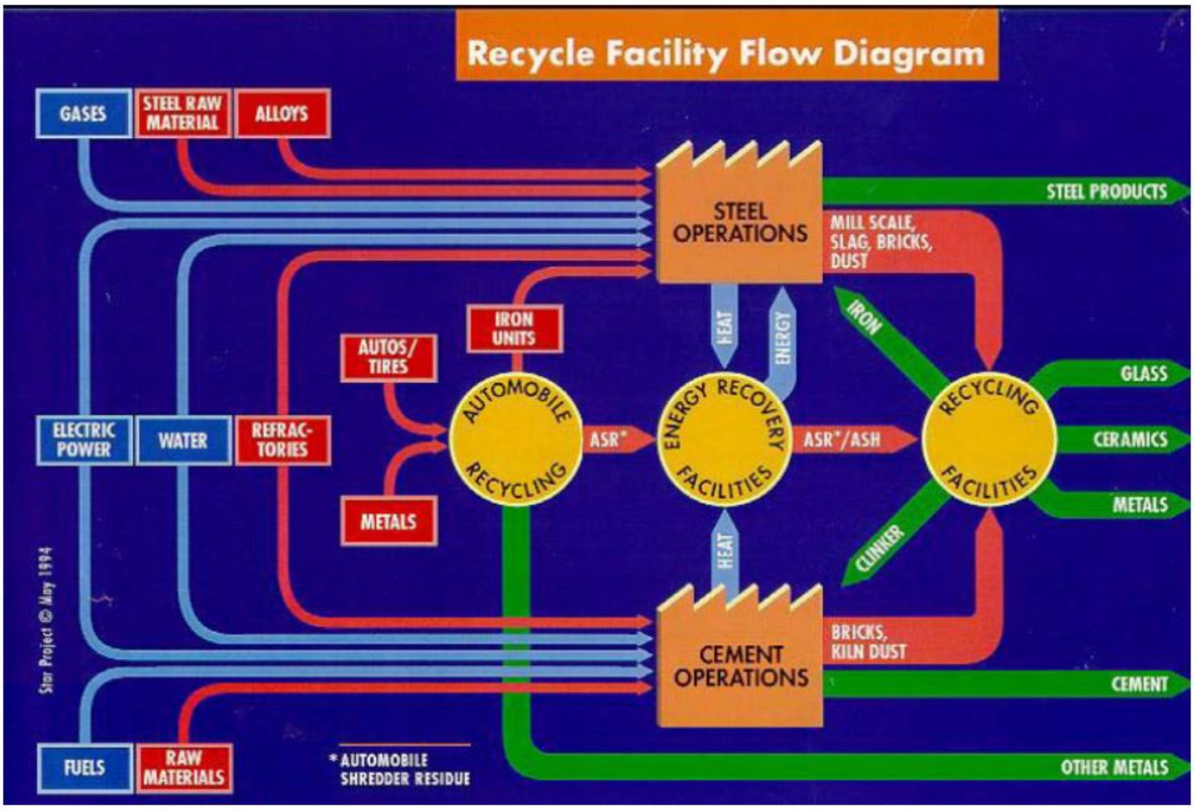
Le projet de symbiose industrielle à Tampico fût initié en 1990, sous la direction de Gordon Forward, chef de « Chaparral steel », membre du groupe « Texas Industries », et proche du secteur de la production de ciment via l'entreprise Portland ciment. Forward révéla un grand nombre de synergies potentielles entre l'industrie de l'acier et celle du ciment. La mise au grand jour des synergies potentielles entre les deux entreprises – notamment la gestion des flux matériels entre déchets et ressources comme intrants - fût rendue possible grâce à l'identification des contraintes techniques et des besoins en ressources humaines.

Au début du projet, la complexité des opérations et le sentiment de méfiance furent dominants, même lorsque les entreprises n'étaient pas en concurrence. Une fois ces obstacles tombés, les bienfaits de la coopération inter-entreprises se sont révélés être très importants, notamment via des échanges culturels et l'identification des synergies potentiels. Le passage de la posture d'isolement entrepreneurial à une nouvelle façon de faire des affaires (partage d'objectifs, échange d'information, recyclage de matériels…) fût ici déterminant (Business Council for Sustainable Developement - US, 2008). La synergie entre les deux entreprises a pris les traits d'un brevet et d'un nouveau procès (du nom de CemStar, qui utilise l'acier comme intrant pour la production des fours à ciment). Ce procès a permis l'obtention d'un ciment de haute qualité. En plus, l'entreprise Portland a pu tirer d'autres bénéfices (croissance de revenus) de la synergie, une réduction des besoins énergétiques (entre 10% et 15%) et une importante réduction des émissions de CO2 (de 10% par tonne de production de ciment). Forward et Mangan ont partagé leurs résultats avec le BCSD, pour démontrer le potentiel de ce type de synergies à l'intérieur du Parc industriel d'Altamira (Business Council for Sustainable Dvelopement - US, 2008).

[13] Source : http://www.wbcsd.org

http://www.wbcsd.org/DocRoot/VvYTNmsJuZwcZxjtYQJ3/USBCSDBPSfullcasefinal.pdf

Figure 13. Diagramme de Flux de Recyclage Parc Industriel Tampico-Altamira 1997-1999



Source: BCSD Gulf of Mexico, 1997

Etape d'analyse et mise en œuvre

Cette deuxième étape commença en 1998, elle fût caractérisée par la participation de deux groupes de recherches (celui de l'Université Autonome Métropolitaine, Analyse et Gestion Socioéconomique des Organisations (AGSEO) et celui de l'Institute Polytechnique National, Groupe de Recherche en Ecologie Industrielle) dont les intentions premières étaient de multiplier le nombre de synergies développées sur le terrain. L'objectif du projet était l'identification des facteurs et des conditions nécessaires pour l'essor de stratégies d'innovation technologique et organisationnelle qui puissent à l'avenir amener des résultats positifs en termes d'écologie industrielle : éco-efficacité, recyclage de matériels et synergies industrielles (Lule Chable, Cervantes Torre-Marín, & Graciela, 2011). Dans cette région, il y a plus de 30 installations industrielles avec une capacité de production de 3 millions de tonnes chaque année. Le pourcentage d'exportation est d'environ 50 ou 60% de la production vers 55 pays du monde. L'investissement est de plus de quatre milliards de dollars et les opportunités de création d'emplois y sont nombreuses. Ce sont aussi les principaux producteurs nationaux en matière de carbone, résine thermoplastique, pigment blanc, PET, PVC et caoutchouc synthétique. La raffinerie, le port et les installations du parc Industriel d'Altamira soutiennent la distribution et production des entreprises membres (AISTAC, 2011). Les flux d'entrée et de sortie des matières, les outils et l'information sur les couts ont été estimés sur mesure. Lors de la première étude, l'eau résiduelle, le dioxyde de carbone et le carbone étaient les trois principaux déchets, avec une production respective de 44820, 44400 et 26720 tonne/année (Carrillo, 2005 ; BCSD-GM, 1999).

29 flux de matières avec 46 modes d'emploi différents ont été identifiés à travers l'étude du métabolisme industriel de l'écosystème Tampico-Altamira. 63 synergies ont été proposées. Après une évaluation technique, légale et financière, 13 d'entre elles (les plus viables) ont été mises en œuvre. Mettre en œuvre des synergies n'est pas une chose facile. Il y a beaucoup de contraintes économiques, normatives et géographiques. Certaines apportèrent de bons résultats alors que d'autres butèrent sur des contraintes technologiques. Un problème posé par le système économique fût clairement identifié, à savoir que le coût environnemental (ou coût dit de pollution) n'était pas inclus dans la structure organisationnelle, ce qui fait que les investissements synergétiques n'étaient pas économiquement viables la plupart de temps.

La distance et le coût de transport des matières identifiées dans les flux de la symbiose d'Altamira constituèrent une contrainte économique forte. La principale barrière normative fût une exigence de reclassification des matières de déchets en raison de ses fonctions potentielles (Lule Chable, Cervantes Torre-Marín, & Graciela, 2011).

Les points forts de la symbiose industrielle de Tampico et plus généralement ceux liés à la mise en place d'un parc éco-industriel ont pu être identifiés:

1. Un rôle important joué par les acteurs publics (ici, c'est la volonté des collectivités territoriales de redynamiser un territoire en difficulté économique) ;
2. Une participation des associations industrielles ou groupes sociaux et collectives ;
3. Une forte intégration de la population locale et des particularismes du territoire ;
4. L'existence de leaders très engagés et charismatiques ; avec compétences en communication et confiance des partenaires ;

5. Un investissement particulier dans tous les projets et une participation des ressources publiques, soit de la collectivité, à un niveau national ou international dans le cas *d'Industrial Symbiosis Programme*.

6. Une facilitation des aspects juridiques et réglementaires par rapport aux projets des entreprises individuelles.

7. Une forte capacité de résilience de la symbiose proprement dite (notamment par la prise en compte du facteur environnemental : volonté des entreprises locales de réduire la pollution et leurs émissions de gaz à effet de serre) ;

8. Une forte synergie entre les entreprises locales et les collectivités territoriales inscrite dans un processus de coopération décentralisée.

Table 6. Démarches de synergies industrielles entre entreprises au Mexique

Code	Dates	Projet	Porteur du projet	Périmètre	Pour aller plus loin
4	2000-Aujourd'hui	Symbiose industrielle	Rural autochtone Ejido -Purépecha	San Juan Nuevo Parangaricutiro	http://web.worldbank.org/archive/website00889/WEB/PDF/6_MEXICO.PDF, http://iasc2008.glos.ac.uk/conference%20papers/papers/O/Orozco-Quintero_127501.pdf
5	2005-Aujourd'hui	Industrie du recyclage mexicain	Coca Cola de México	Boulevard Mexique-Querétaro	http://dcsh.xoc.uam.mx/ecocambiotec/TesisMaestria/82AlvaradoRaul2009.pdf
6	2008-Aujourd'hui	Bouclage de flux	Tannerie Industrie	Léon, Guanajuato	http://148.206.107.15/biblioteca_digital/estadistica.php?id_host=6&tipo=ARTICULO&id=4850&archivo=1-309-4850anx.pdf&titulo=Econom%C3%ADa%20ecol%C3%B3gica%20frente%20a%20econom%C3%ADa%20industrial.%20El%20caso%20de%20la%20industria%20de%20la%20curtidur%C3%ADa%20en%20M%C3%A9xico.
7		Bouclage de flux	Multiple use de la forêt tropicale pour les autochtones	Sud et Sud-est mexicain	http://www.ecologyandsociety.org/vol7/iss3/art9/

Un tel exemple (Tampico) démontrerait que l'écologie industrielle et territoriale s'inscrit dans les stratégies de développement durable des territoires tout en proposant un modèle de développement alternatif aux pays du Sud. A l'heure où le Mexique ouvre son marché de l'énergie à la concurrence et envisage de développer les énergies renouvelables (principalement la biomasse), l'écologie industrielle et territoriale, calibrée sur la formule du «

moins c'est mieux », pourrait de plus en plus s'imposer comme une stratégie viable pour le Mexique et les pays du Sud, plus généralement.

CONCLUSION

L'écologie industrielle et territoriale peut s'apparenter à un modèle de coopération décentralisée dans lequel les flux de matières, d'énergie et d'informations sont optimisés et dans lequel les parties prenantes sont impliquées dans le bon fonctionnement de la symbiose. Cet article fait partie d'une étude réalisée sur trois symbioses[14] , Kalundborg (Danemark), Dunkerque (France) et Tampico (Mexique). Les quatre postulats (éco-efficacité, collaboration, proximité et résilience) de la durabilité forte doivent être mis en parallèle avec trois méthodologies complémentaires utilisées pour la circonstance. (i) Une analyse systémique reposant sur la dynamique des systèmes (initiée par les travaux de J.J Forrester, 1965 et le rapport Meadows, 1972). Contrairement aux schémas de flux, couramment utilisés pour présenter les échanges de matières, d'énergies et d'eaux, la dynamique des systèmes insiste sur les boucles positives et négatives amplifiant ou régulant la symbiose. (ii) Une grille d'entretiens visant à appréhender les postures des acteurs (objectifs, attentes, stratégies, actions…) par une matrice SWOT, à analyser les discours des différents protagonistes (utilisation du logiciel TROPES) et à cerner (chronologiquement) l'histoire de la symbiose de Tampico. (iii) Le recours aux cercles de soutenabilité de Paul James (2015). Si cette approche relève principalement de l'écologie urbaine (titre de l'ouvrage *Urban Sustainability in theory and Practice)*, nous montrerons qu'une organisation comme la symbiose industrielle peut être analysée grâce à cette grille de lecture.

En replaçant le territoire au cœur des stratégies industrielles, les symbioses pourraient bien se substituer aux politiques d'industrialisation libérales (ouverture à la concurrence) prônées par les institutions internationales (Banque Mondiale, FMI, OCDE…) en ré-encastrant l'économie et la technologie dans les limites biophysiques de l'environnement.

[14] Ce travail est actuellement réalisé dans le cadre d'une thèse de Doctorat par Manuel Morales

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SECTION II - LITERATURE REVIEW

CHAPTER 2. STRONG SUSTAINABILITY AND POSTULATES IN TERRITORIAL AND INDUSTRIAL ECOLOGY

Servitization in Support of Sustainable Cities: What Are Steel's Contributions and Challenges?

sustainability

MDPI

Article

Servitization in Support of Sustainable Cities: What Are Steel's Contributions and Challenges?

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Abstract: In the pursuit of eco-efficiency, resilience, and self-sufficiency, sustainable cities focus on long-term environmental goals instead of only short-term economic ones. To do so, many of them rely on servitization, the practice of replacing tangible solutions for intangible ones. Considering steel's wide range of applications and its pervasive presence, this article's goal was twofold: Not only to understand how servitization helps sustainable cities, but also the contributions and challenges of the steel present in service-providing. To do so, the criteria of sustainable urban metabolism and circles of sustainability were used to analyze three case studies of servitization: energy, housing, and mobility. The results showed that servitization can provide significant benefits to sustainable cities, while also being able to substantially alter the supply-side dynamics of steelmaking by affecting, most notably, demand. This brought to light how important it is for steelmakers to pay close attention to the service-providing initiatives that may concern their clients and products. Nevertheless, further research is necessary to fully understand all of the effects that servitization can have on all of the commodities involved in its implementation.

Keywords: servitization; sustainable cities; steel; circles of sustainability; sustainable urban metabolism

INTRODUCTION

A healthy environment, social cohesion, and economic efficiency are trademarks of a sustainable city, a political entity that defies market dynamics by prioritizing long-term political goals instead of short-term economic ones, focusing on eco-efficiency, self-sufficiency, and circular environmental management [1–5]. One of the tools available for sustainable cities and the industries within it to manage their resources is servitization: The practice of reducing material needs by changing a product's ownership or its presence altogether in favor of providing a service or solution [6–8].

Although certain forms of servitization (e.g., public transportation, vehicle rentals, shared housing) can already be seen in most modern societies, most research efforts are dedicated to implementing the services themselves on the demand-side, and not to further understanding their effects on the supply-side of the materials and resources involved [6,9]. Although innumerable materials are part of a society's metabolism, this article focuses on steel, one of the most prevalent commodities that, as present it may be, has its supply chain often dismissed along with that of other primary and secondary materials when focus is given to service-providing alone [7].

In order to better understand the potential contributions of steel and the challenges it faces when interacting with servitization to help improve urban sustainability, this article used two tools—sustainable urban metabolism and circles of sustainability—and supporting bibliography to quantitatively and qualitatively analyze three case studies that exemplify successful applications of servitization.

1.1. Sustainable Cities: Cells of a Larger Organism

The historic conceptual evolution of sustainable cities was based on that of sustainable development—a term that later gained political connotations with the Brundtland Commission— and which can be traced back to 18th century forestry management in Germany [3,5,10]. In the report Our Common Future, sustainable development was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [11]. At that time, the idea of a "sustainable city" was an automatic derivative related to urban development policies.

By the 90's it was fleshed out in the Aalborg Charter [12] by more than 700 cities worldwide, and in the Melbourne Principles of the Local Agenda 21 [13]. From then on, the concept of a sustainable city grew and, in practice, became strongly intertwined with the idea of a triple bottom line—or three pillars—denoting a close relationship between economic, social, and environmental sustainability, with a combination of indicators to measure each of them [3,5,14].

Meadows [15] and Brugmann [16] approached the term from a more environmentally-oriented perspective and proposed that it should include indicators for pollution and carbon emissions, water consumption and quality, energy mix and demand, waste management, green built environment, and forest and agricultural land management. Burdett and Sudjic [17], on the other hand, adopted a more socio-economic interpretation, in which social equity alongside a greener living environment should be considered for the development of sustainable cities, also suggesting that cities should offer proximity, density, and variety enough to engender productivity benefits for firms and help stimulate innovation and job creation.

The overall mindset began to change at the beginning of the 21st century when Rogers [18] conceptualized a sustainable city as a place where a higher quality of life is realized in tandem with policies, which effectively reduce the demand for resources and draw from the city's hinterland to become a more self-sufficient and cohesive economic, social, and environmental ecosystem. As autonomous as a cell can be, a sustainable city is unable to live fully independently outside the organism of its nation; therefore, renewed attention was then given to some of the economic aspects of sustainable cities, rekindling the academic interest in contributing to policy-making, notably on the transitional and structural measures necessary to shift the interactions between urban stakeholders, from linear and production-oriented to circular and service-oriented ones [5,19].

Keeping in mind that the urban-level approach of sustainable cities provides tangible applications, easier implementation, and reduced monitoring complexity, when compared to approaches in regional or national scales all the while supporting their results as well [3–5], the next section of this article introduces one of the tools capable of contributing to resource efficiency and management bottom-up.

1.2. Servitization: Demand-Side Circularity from Within

The term servitization was created to describe the idea of product manufacturers, wholesalers, and retailers reducing their tangible portfolio in favor of an intangible one [20,21]. Currently, the application of this concept is closer to its origin in the 1980s, in which the idea was to deliver to the customers a package of services, goods, support, and knowledge that together represent a solution, and not only a sale [7,22,23]. Most modern companies adopt it in either the stages of pre-sale (e.g., trials, demonstrations, and custom design); sale (e.g., installation and training); or post-sale (e.g., maintenance, support, and warranty) [24,25].

Nevertheless, actual reductions in the overall amounts of resources and energy consumed usually derive from services that actually shift product ownership or that do not require the customer to acquire the product in the first place, instead of buying the results or benefits it delivers (e.g. leasing, renting, and pooling) [26,27]. In 2009, 84.8% of manufacturing companies offered services to support their products, being only 12.1% of those directly related to the changing product ownership or to a product being operated by the manufacturer as a service to the customer [28,29].

Although well aligned with concomitantly developing concepts, such as circular economy, the servitization trend evolved in parallel and gained its largest share of attention after the photocopier industry decided to lease or rent their multifunctional products to foster a pay-per-printed-page solution, instead of a one-photocopier-per-office business model [20]. Once customers started perceiving direct or indirect financial benefits, this phenomenon opened the doors for discussions in all related matters: From the potential innovations in business models to the psychology of product ownership; from unique selling propositions (USPs) to sustainable resource management and product-service systems (PSS) [23,30,31].

Service-providing initiatives then became commonplace in marketing management, focusing almost exclusively on the costs being reduced in the search for profit, while giving little to no attention to the resources being saved [9,32]. Although headed in the right direction from an environmental standpoint, this counterintuitively went against some of the principles of sustainability: Selling services without addressing their resource demands ended up, in some cases, increasing material consumption [6,8]. It was when academics, involved in what is called redistribution and sharing within the circular economy framework, drove their attention to service-providing practices already in place that servitization found new grounds and began receiving more support as a means to retain resources longer in the economy, creating value from service and circularity instead of value from natural resource extraction [9,33,34].

Although the variety of resources that circulate within a given society can be theoretically infinite, this article focuses on steel, a commodity with significantly different dynamics from those of the service sector, but that nonetheless counts on plenty of intersections with servitization applications.

1.3. The Role of a Commodity in a Service Economy

Steel is a key commodity in global economies, continuously increasing in use per capita—steadily from 204.6 kg in 2011 to 214.5 kg in 2018—due to its wide range of applications: from home appliances to cargo hauling, from construction to telecommunications [35–37]. Steel's life cycle starts when iron ore is mined and it ends either within built structures with long lifespans or by being recycled as scrap, most of its environmental impacts being related to the use of non-renewable energy sources and the consequent effects on the climate [38–40].

The steel industry alone is responsible for approximately 6.5% of worldwide CO_2 emissions [41] and it consumes substantial amounts of coal, as seen in Figure 14. In order to achieve the SDGs, it is estimated that the steel industry worldwide would need to increase the use of electricity from the current 26% to 40% by 2030 [42].

Notably in the last decade; however, the steel industry has been facing difficulties regarding prices, energy, trading, and competitiveness – all understood to be hindering environmental progress regarding emissions and resource efficiency [43]. Consequently, multiple academic, institutional, governmental, and industrial experts have highlighted the need for this industry to have an active role in expanding and improving end-of-life markets, mostly to increase production based on steel scrap to support a transition towards the use of electricity instead of coal [43].

Due to the its products' and its raw materials' physical and chemical characteristics and requirements, the steel industry has traditionally given substantial attention to variables that boost or hinder the quality, quantity, and profitability of its outputs, being one the pioneering industries to apply some of the environmental principles of circular economy and sustainable development—mainly recycling and by-product reuse [43,44].

As important as recycling is—capable of saving 1.400 kg of iron ore, 720 kg of coking coal, and 120 kg of limestone per ton of recycled scrap, on a global average— and even though record-breaking sums of capital have been directed towards environmental goals, minimal attention has been given to redistribution, sharing, or servitization, despite 65% to 80% of investments being focused on end-of-life solutions [43,45–49]. And policy wise, regardless of how significant the results of servitization, sharing, or redistribution have been when implemented [44,50], no examples of direct policy-based stimulus or guidance has been found by the authors to support service-based practices capable of allowing this industry to contribute to the sustainability of an urban environment.

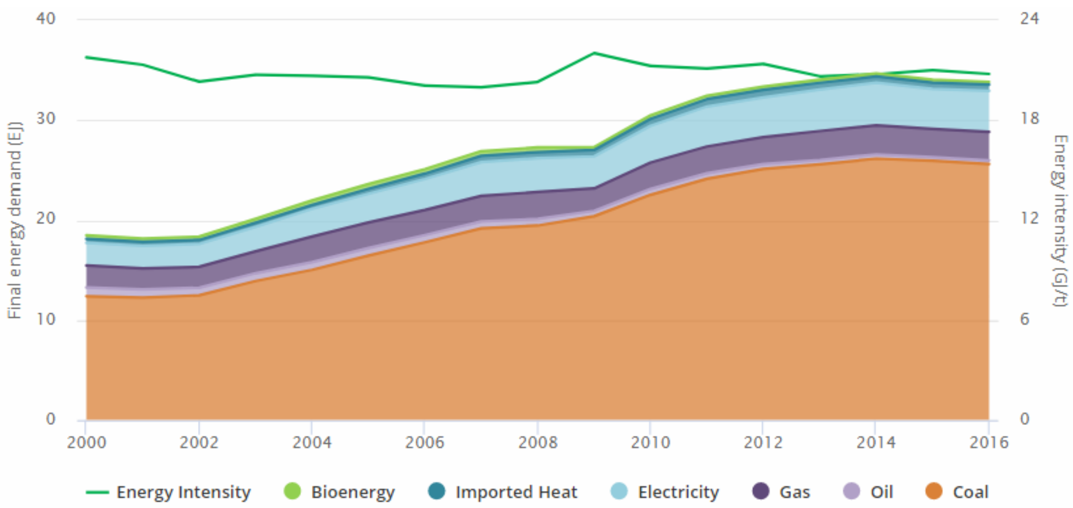

Figure 14. Steel's energy intensity and demand [42].

It was with this context in mind that the authors chose this material as the object of exploration for better understanding how servitization can affect the supply-side dynamics of sustainable cities and; therefore, contribute to environmental progress. In the aforementioned photocopier example alone, the reduction in total demand for the specific steel components necessary for these machines to operate configures, in itself, a fitting argument for how servitization can be a tool for reducing natural resource exploitation when its effects are passed along the steelmaking supply chain.

Along with the other commodities present within the goods potentially targeted by servitization, steel's presence in service-oriented projects would be, even if indirectly, a factor capable of affecting, for example, (a) the importance of steel products' quality and durability; (b) the quantities, quality, and accessibility of recyclable scrap; (c) the development of other end-of-life and circularity services such as repair, maintenance, reuse, sharing, refurbishment, and remanufacture; and (d) the gradual shift towards operational longevity instead of component replacement, counteracting trends of planned and designed obsolescence.

METHODOLOGY

This article aims to understand the potential contributions that steel could bring through servitization to a sustainable city as well as the challenges steel could face while attempting to do so. This study's contributions derive mostly from approaching the potential benefits of servitization to a sustainable city from the supply-side perspective, focusing on how such a commodity's supply chain operation could improve in order to better support, through service-providing, the environmental aspects of an urban metabolism.

The first step taken was evaluating and analyzing what were the contributions that three successful case studies on servitization would provide to a sustainable city; then, steel's participation was identified within each of the case studies and its respective contributions and challenges were discussed.

2.1. Tools

Assessing the behaviors, performance, or structure of sustainable cities is a task that can be carried out by substantially different approaches, methods, and tools. Given this article's focus on servitization and on the steel within it, the authors opted for the ex post use of two tools: a quantitative one (sustainable urban metabolism) and a qualitative one (circles of sustainability).

As detailed next, these tools were chosen based on their different approaches to stakeholders' involvement, eco-services, and eco-efficiency. While the first one provides quantitative support for decision- and policy-making based on urban ecosystems theory, the second one is intended to be flexible and modular in order to align empirical solutions to the social conditions that permeate them [18,51,52].

2.1.1. Sustainable Urban Metabolism

The underlying principle of urban metabolism is the conservation of mass towards the transformation of industrial activities in an urban environment, from what is largely known as non-sustainable and linear systems to what would resemble sustainable and circular ones [51]. As seen in Figure 15, it begins by employing material and energy flow analysis (MFA and EFA, respectively) for the identification and quantification of material and energy usage, as well as assessing their impacts on the environment [53].

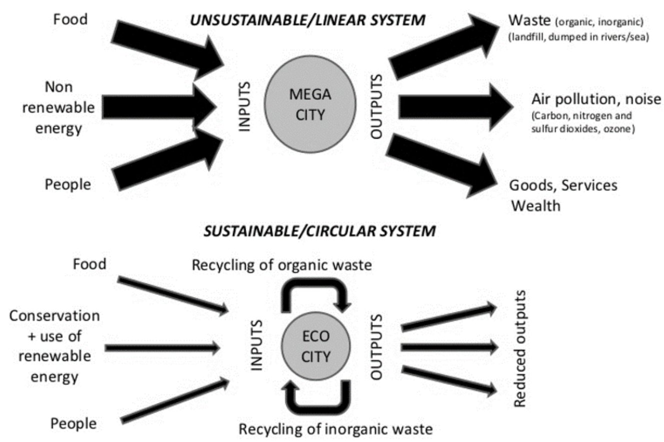

Figure 15. The city as a system [52].

This metabolic assessment takes into account the basic consumption of the households within a city—such as heat, electricity, water, and food—and links them to the local means of production that have corresponding benefits in terms of local economy, employment, greenhouse gas reduction, etc. Depending on the intensity of the flows of each resource and on how they evolve through time, the urban metabolism can gradually shift to patterns of zero waste, positive energy, closed water cycles, etc. [18,54].

From that point on, having a clearer holistic and systemic understanding of a city's metabolism, measures for delivering improvements to each of the subsections of the assessment become the focus [18]. Finding ways to balance inputs and outputs among the multiple stakeholders involved naturally includes social and economic aspects, thus stimulating the development of new technologies and business models capable of reducing stocks and improving circularity, without negatively affecting quality of life and wellbeing [18,54].

This article's use of this tool considers the before and after conditions of inputs, outputs, stocks, and flows in the context of each case study, aiming to identify how each case study was able to affect sustainability by empirically altering the amount of materials or energy present in the urban environment they were a part of.

To do so, the initial and final amounts of steel embedded in the servitization solutions deployed by each case study, as well as the energy used to produce it, were identified and calculated and, based on their sources, flows, stocks, and sinks, evaluated regarding their effects on sustainability along with the next tool.

2.1.2. Circles of Sustainability

Circles of sustainability, on the other hand, focuses less on quantitative and more on qualitative aspects of a city's metabolism. Although it encompasses environment and economy for the purposes of flow optimization, its main attributes are the intersections it provides with social conditions such as resilience, cooperation, and proximity within a community [52,54]. This tool is intended to be flexible and modular, and addresses the four domains of ecology, economics, politics, and culture by dividing them each into seven key aspects, all with their own criteria for conducting discrete semi-directed interviews with key actors and stakeholders of a city, resulting in the nine-points scale of seen in Figure 16 [52,54].

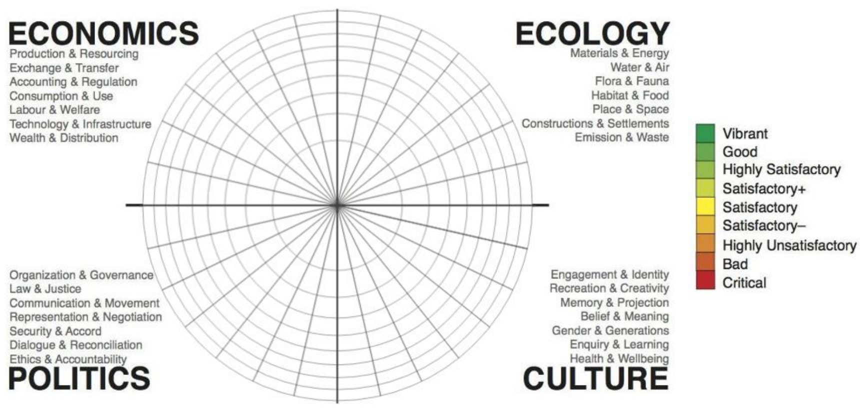

Figure 16. Circles of sustainability [52].

Multiple cities (e.g., Melbourne, Porto Alegre, Milwaukee, and New Delhi) have assessed their sustainability using this tool, enabling not only a diagnostic understanding of their situation, but also the intake of feedback and knowledge from the participation of their industries, communities, and decision-makers [55]. In Johannesburg, it helped its Department of Transportation to redefine public mobility goals; in Port Moresby, it helped the municipality in finding new solutions to land use management issues concerning informal employment and ethnical disputes; and in Valetta, it improved the understanding of the cultural obstacles and political barriers responsible for hindering the development of an educational system to be capable of retaining qualified workforce [55].

In this article, this tool was used to identify where within the domains of a sustainable city each case study's contribution would help improve sustainability and, in conjunction with the previous tool, to which extent these effects were linked or not to the presence of steel. Whenever and wherever steel's presence was identified within the domains of a sustainable city as per each case study, and having already applied the previous tool for identifying and measuring the quantitative aspects of steel's participation in each case study, the authors then used the criteria of circles of sustainability to evaluate how impactful the quantitative changes in steel would be to the qualitative aspects of sustainability.

2.2. Case Studies

Three case studies, focusing on different applications of servitization principles, were chosen for this study: energy [56], housing [57], and mobility [58]. All case studies are described below and have four aspects in common: (a) Being based on real life applications; (b) seeking benefits and improvements from an environmental and sustainability perspective; (c) considering the policy and social factors of the context in which they are inserted; and (d) discussing their results not only in present terms, but also in perspectives for future contributions. The authors believe each of the case studies illustrates a different role that steel can play when servitization is used towards improving sustainability.

2.2.1. Energy

In an urban environment, electricity not only supplies industrial and commercial activities, but also guarantees particular levels of provision, such as lighting, room temperatures, and humidity control [59]. Servitization in energy is; therefore, a conjunction of energy supply and energy-related services aiming at efficiency, savings, and sustainability [60–62]. It can also refer to outsourcing and decentralization processes, involving third-party contractors for distribution and maintenance or even the deployment of energy generation technologies directly onto a customer's property, often creating potential for energy feedback to either grid or supplier [63,64].

A good example of decentralization based on electricity feedback to the grid was developed by Pinto et al. [56], in which photovoltaic solar panels installed on the roof of houses of a social program were shown not only capable of creating energetic independence for home owners facing a structural national crisis, but also of reducing overall generation demand due to the creation of localized electricity feedback networks when given proper policy support.

The study considered three different electricity consumption scenarios for houses in five different regions of Brazil, keeping in mind specific solar irradiations, quantity of panels, costs of deployment, generation potential, and sensitivity analysis. Results indicated monthly bill savings between 8% and 52% per house, with potential electricity feedback to the grid up to 47% under adequate policy support [56].

2.2.2. Housing

Developing sustainable housing is an essential component of sustainable cities, not only because globally over one-third of all final energy and half of electricity are consumed by housing and generates approximately one-third of global carbon emissions [65], but also because multiple aspects of housing directly affect inhabitants' health, comfort, wellbeing, quality of life, and workforce productivity [66]. Sustainable housing is designed, constructed, operated, renovated, and disposed of in accordance with ecological principles for the purposes of minimizing the environmental impact and promoting occupants' health and resource efficiency [67].

Although retrofitting (i.e., upgrading existing buildings to improve their energy efficiency and decrease emissions of greenhouse gasses) seems to be technically viable and sometimes economically attractive, multiple barriers prevent optimal applications [68,69]. Servitization of sustainable housing takes into account the entire life cycle of a building in an attempt to re-use, recycle, and upcycle by means of, for example, the adoption of design-for-disassembly of individual parts and components that need to be fixed or replaced.

In their study, Céron-Palma et al. [57] focused on the operation stage of a house (i.e., while citizens inhabit the building), proposing measures to reduce emissions linked to energy consumption and to decrease food dependence with the subsidized replacement of standard appliances with eco-efficient alternatives and by creating green spaces and productive gardens. The study collected consumption data to feed a Life Cycle Analysis model that encompassed all operational aspects of living in that environment in Merida, Mexico (e.g., products' packaging, and material logistics).

After testing six different scenarios, results indicated that replacing appliances with more eco-efficient alternatives and making use of a green space or garden for food cultivation could save an average of 1 ton of CO_2eq emissions every year per house (i.e., 67% less emissions than a standard Mexican home) [57].

2.2.3. Mobility

The transport sector consumes 2,200 million tons of oil equivalent, accounting for about 19% of global energy demand and for 24.3% of the greenhouse gas emissions [70]. Consumption is expected to increase by between 80% and 130% above today's level until 2030 and, unlike other sectors—which decreased their emissions by circa 15% between 1990 and 2007—transportation increased it by 36% during the same period [70].

Servitization in transportation contributes the most to sustainable cities in terms of sustainable urban mobility (SUM), a transport model that stimulates interaction among all involved stakeholders in order to develop a comprehensive mobility service offer that responds to citizens' needs for flexibility and convenience, door-to-door, removing the need for vehicle ownership by combining different shares of, for example, public transportation, car-sharing, taxis and shared taxis, bicycle and bike-sharing, car-pooling, or park-and-ride [71,72].

Diez et al. [58] focused on the city of Burgos, Spain, in which fifteen different measures were put in place in 2005 by a CiViTaS project initiative. Measures included (a) switching public transportation to biodiesel; (b) increasing the amount of pedestrian-preferential areas; (c) underground parking areas; (d) higher capacity public transportation vehicles; (e) schedule alignment between different transportation methods; (f) bicycle lanes, rentals, parking, and bike-sharing; and (g) restrictions on heavy load traffic.

The city saw multiple positive results in the span of five years, mostly related to citizen behavior transition towards bicycles and public transportation instead of private vehicles [58]. When considering a twenty-year period, up to 47,000 tons of CO_2eq emissions were expected to be avoided at the expense of €7.2 million in investments, well within estimations of European authorities for funding similar projects [58].

RESULTS

This section presents the knowledge acquired from evaluating and analyzing each servitization application towards the improvement of sustainability in an urban environment. Each case study was subjected to ex post application of the tools described before and their key attributes were identified along with steel's contributions and challenges.

3.1. Energy

The servitization of electricity once bought as a product and delivered to a household merely for consumption into a localized and demand-specific solution, capable of reducing costs and adding consumer value, as seen in the study by Pinto et al. [56], relied on two different factors: (a) Replacing a mostly hydraulic-based grid electricity supply with decentralized solar sources, and (b) retaining, redistributing and reusing excess energy within the local network by using feedback. The first factor contributes to reducing electricity demand from the installed capacity while reducing the demand for electricity distribution along the grid. On the other hand, the second factor not only contributes to the previous one, while providing economic benefits to the citizen, but also adds intangible values such as grid independence, community integration, and participation.

From the perspective of sustainable urban metabolism, the propositions of Pinto et al. [56] help to partially transfer electricity sourcing from outside a city's boundaries to the households within it, directly reducing the required external energy input while strengthening and empowering local stakeholders at the expense of an increase in material stock within the city's boundaries. Furthermore, it reduces the amount of electricity wasted by over-generation as well as electricity lost during long range distribution. Cities in which such a project would be deployed would become altogether more resilient and sustainable while helping reduce emissions, losses, and wastes related to electricity generation.

When applying the criteria of circles of sustainability to this case study, several contributions were identified, as seen in Figure 17. In the domains of politics and culture, minor benefits to organization and governance and engagement and identity were perceived, respectively, related to the required policy adjustments that would enable grid feedback and feed-in tariffs, and to the creation of a local community of households of which roofs now include solar panels.

It was in the ecology and economy domains; however, that most contributions were perceived. Deploying photovoltaic solar panels onto the roofs of Brazilian households could significantly shift how electricity is used and consumed in relation to its existing matrix, potentially creating new service sector jobs related to installation and maintenance. Moreover, improving infrastructure by using new technologies is a good way to increase local wealth distribution, while promoting or changing how knowledge and capital are exchanged. Additionally, having a network capable of grid feedback also increases the need for proper and engaged accounting and regulation, especially if the study’s proposition of feed-in tariff cross-discounts is put in force.

Changing how electricity is generated also changes the materials necessary for the equipment used to generate it. Photovoltaic solar panels use considerably more silicon than iron in their composition, for example, in addition to other materials less pollutant to produce or less impactful to implement than hydraulic energy infrastructure. Consequently, both direct and indirect benefits to air quality, water quality, and reductions in the amounts of emissions and waste generated would be perceived throughout the entire system, thus improving the sustainability of the urban area it would be a part of, while potentially reducing the need for environmental impacts outside its boundaries as well.

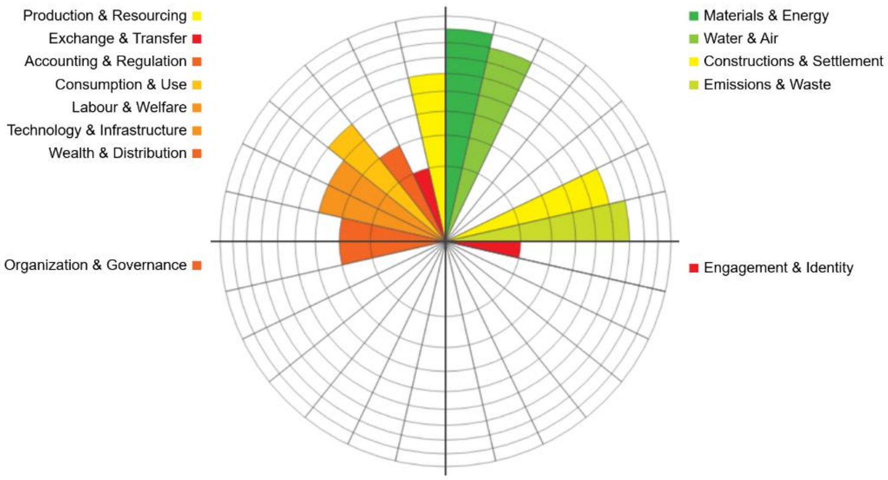

Figure 17. Energy case's perceived key contributions to sustainability.

Although steel presence in photovoltaic solar panels is minimal—around 3%, in the frame and in the installation hardware, consisting mostly of stainless alloys UNS S30400 and S31600 [73]—it is important to note that the mainly hydraulic Brazilian energy matrix relies heavily on energy generation equipment made of steel and, even if the distribution itself depends mostly on copper and aluminum, steel-intensive machinery and structures are always present [74–78].

The results available in the study by Pinto et al. [56] point to an average of 153.25 GWh generated by 405,691 solar panels installed onto the roofs of 73,762 houses, the equivalent of the entire electricity generation capacity of the Jupiá hydropower plant in Três Lagoas, Brazil [75]. Considering that an average hydropower plant contains 10,000 tons of steel in its structure [74] and taking into account an average photovoltaic solar panel mass of 18 kg [76,78], the participation of the steel present in the solar panels is about 0.7 kWh/kg of steel, while the participation of the steel present in the hydropower plant would be of approximately 0.015 kWh/kg of steel—45 times less.

It is important to note; however, that solar panels cannot produce electricity 24 h/day, thus requiring either energy storage or additional energy sources to fully supply the demands of a household. Considering the use of lithium ion batteries and only 10 h/day of solar irradiation, the previous result in the participation of steel in electricity generation falls to 0.24 kWh/kg—still 16 times better than hydropower alone for a period of 30 years of operation.

Furthermore, considering an energy intensity of 22.5 GJ/ton of steel [79], producing all the solar panels and the required amount of batteries for this case study would consume approximately 5.35 TJ, while building the equivalent hydropower plant would require around 225 TJ for steel alone, with the notable addition of stronger and more complex alloys such as UNS S32205 and S S17400 [73].

This indirect reduction in supply-side steel intensity per kWh generated, coming as a result of demand-side servitization, points to one of the potential contributions of steel—in this case related to its quantity; although less steel is present, its participation is substantially more relevant. The challenge for steel, in cases like this, resides mostly in identifying where is the least amount of steel capable of providing the most environmental benefits (e.g., small amounts on a solar panel provide more environmental value than very large amounts in a hydropower plant).

3.2. Housing

By subsidizing a transition towards eco-efficiency within households and supporting it with maintenance—whether if by leasing or not—a city can turn appliances, previously acquired by its citizens merely as products to be used and discarded, into solutions capable of actively supporting the reduction of its required energy inputs as well as its emissions. Servicing this equipment and further supporting this initiative with the creation of green spaces and gardens capable of providing food, and consequently reducing the amounts of packaging, food waste, and transportation, poses as a solid contribution to sustainability.

As per sustainable urban metabolism, the study from Céron-Palma et al. [57] contributes to reducing inputs and outputs, but minimally—if at all—to reducing stocks. The reduction of inputs derives mostly from the green spaces and gardens producing food and avoiding the need for packaging and transportation, while the reductions in outputs are most expressive regarding the energy savings provided by eco-efficient appliances and the consequent reduction in emissions. Céron-Palma et al. [57] also present the possibility of carbon sequestration in the green spaces and gardens, but with almost negligible effects relative to the other benefits.

Although the amount of materials and food in stock would likely be unaffected, use and consumption patterns would change and so would production and resourcing, as per the criteria of circles of sustainability. As summarized in Figure 18, minor effects on most of the aspects of the economic and political domains would nevertheless provide substantial improvements in the ecology domain. These improvements would be directly related to increases in health and wellbeing, while contributing – even if marginally – to the creation of a locally-engaged community.

The intersections that exist between all of the aspects of the ecology domain ended up boosting each other; therefore, increasing environmental quality. This points to a reinforcing behavior which, whether intended or not by Céron-Palma et al. [57], presents major long-term sustainability and resilience benefits; the less issues with emission and wastes, the better water and air, which by itself helps improve flora and fauna and habitat and food. Finally, place and space improve as well, boosting health and wellbeing and fostering engagement and identity within the local community, effects of which feed back to the beginning.

As interesting as this behavior may be, its impacts on emissions are less substantial than those of the eco-efficient appliances, highlighting the importance of both being deployed in tandem. Since steel is not present in the green spaces and gardens, and that the case study does not specify which are the types of food produced therein, nor if those are traditionally contained in steel cans and other steel containers, focus was given to the eco-efficient appliances when addressing the participation of steel in emissions. All other variables of the case study’s life cycle analysis were assumed unchanged, meaning eco-efficiency had no effect on the amount of steel content of each appliance. This choice was made due to the theoretical infinite number of possibilities by which eco-efficiency can be achieved by different manufacturers in different models of each appliance.

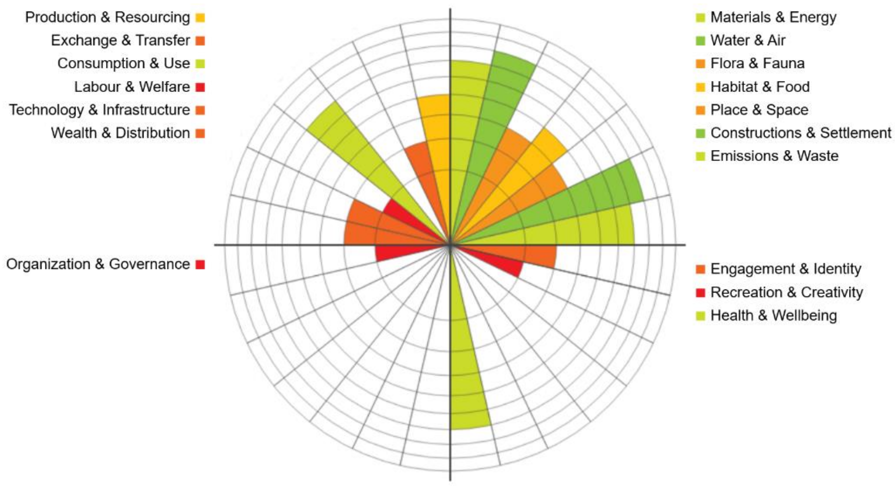

Figure 18. Housing case's perceived key contributions to sustainability.

According to the results from Céron-Palma et al. [57], replacing standard appliances with more eco-efficient ones reduced energy consumption by approximately 46%. Considering an average steel content of 60% per 140 kg refrigerator, 35% per 76 kg washing machine, and 46% per 37 kg air conditioning unit [80–84], the calculations showed that steel's participation in annual emissions per house was reduced by 32% on average, as a result of changing to eco-efficient appliances. More specifically from 4.90 to 3.35 kgCO_2eq/kg of steel (refrigerator), from 1.90 to 1.30 kgCO_2eq/kg of steel (washing machine), and from 84.67 to 57.76 kgCO_2eq/kg of steel (air conditioning unit).

These results grow in significance when keeping in mind the case study's scope of 112,000 houses, resulting in the same 322 TJ to produce all the steel involved, generating 176.74 Mt of CO_2eq emissions, instead of 259.06 Mt. In this case, even though the amount of steel per appliance and the energy used to produce it remained the same, steel's contribution would not reside in its quantity, but in the type of steel and in how it is used in an appliance, for example, towards improving its eco-efficiency during the use phase.

Although this demand-side servitization initiative has minor effect on supply-side scale, the steelmakers' challenge would be to decide on which type of steel to produce (e.g., alloys with better electrical conductivity) and how to ensure its optimal use in a product. Traditional use of steel in appliances revolves mostly around stainless or tool steels used in motors and structural segments, such as UNS S30400 and S43000. In eco-efficient appliances, steel use would tend to revolve more around electrical and tool steels similar to those present in electronics [73], thus changing the alloying requirements of production.

3.3. Mobility

After five years of the implementation of the CiViTaS project in the city of Burgos, a clear change in its citizens' mobility behavior was noticed: It successfully stimulated approximately 10% of its population to transition from either walking or owning a private car towards using either more public transportation, bicycles, or lighter vehicles such as motorcycles [58]. Considering bicycles and, notably, public transportation were provided as a service by the city for the population, and that these means of transportation are less—if at all—pollutant in comparison to cars, servitization has proven itself environmentally friendly once again.

Even considering an increase of 1% in the use of motorcycles and a 6% reduction in the amount of people who preferred to walk their commutes, emission results were very favorable, pointing towards a successful mobility solution proposition that positively affects urban environment. Keeping in mind that bicycles now have their dedicated lanes, and that buses and motorcycles contribute to reducing overall traffic in comparison to cars, this mobility solution also presents medium- to long-term sustainability benefits.

Using the criteria of sustainable urban metabolism, it is possible to identify that the study conducted by Diez et al. [58] altered the city's inputs and stocks, by affecting the composition of the city's mass balance due to the different types of vehicles being used. Consequently, the flows related to mobility and transportation are rendered more efficient, still overshadowed; however, by the notable effects that takes place among the outputs. By changing the mobility matrix, not only do different materials become part of the urban system, but also different and more sustainable sources of energy gain traction: Less cars meant that gasoline and diesel gave way to buses' biodiesel, for example.

With less of their income being used to own a car, wealth and distribution improved from the citizens' perspective, as per the criteria of circles of sustainability, as seen in Figure 19. Improving aspects of the political domain, related to organization and communication, would not only move use and consumption towards a more sustainable behavior, but also help shift production and sourcing and to promote exchange and transfer of more sustainable knowledge and goods. More transportation services would also require more jobs related to operation and maintenance instead of car parts replacement, even if improvements to technology and infrastructure would be minor.

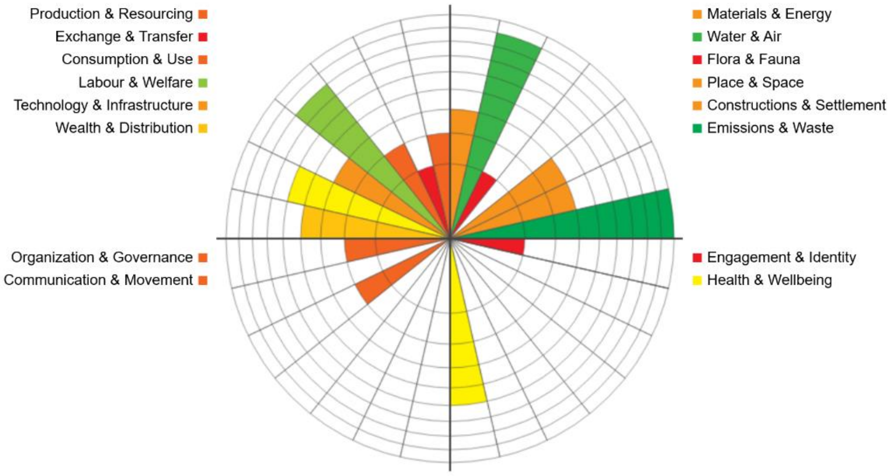

Figure 19. Mobility case's perceived key contributions to sustainability.

The key contributions, nevertheless, are present in the ecology domain: Measures that help reduce traffic—which relate to construction and settlement—further help reduce emissions and contribute to citizens' perception of place and space, due to better water and air, altogether boosting health and wellbeing in the culture domain as well. Therefore, this study configures a good example of sustainable urban mobility, well aligned with the idea of a sustainable urban metabolism.

Having changed which vehicles are used and the frequency of their usage, the study indirectly changed how steel is present in the city as well. Considering that cars, buses, bicycles, and motorcycles are built with different types of steel in different amounts—on average 900 kg, 6000 kg, 6 kg, and 70 kg, respectively [85–87]—not only do the total amounts of steel change, but also their participation in the emissions that occur as a consequence of their presence.

Although using more buses, bikes, and motorcycles caused the amount of steel and the consequent consumption of energy for its production to increase by approximately 18.23% to 82.5%, of which inside buses—having steel be a part of vehicles that are less pollutant than cars or that are more efficient due to their capacity or fuel—caused steel's participation in annual emissions to decrease by 29.6%, from 11.93 to 8.40 kgCO_2eq/kg of steel.

This increase in steel presence associated with lower participation in emissions highlights the importance of defining when and where to use steel, especially considering that the types of steel used for buses—typically UNS S30400, S31600, S40900 and S43000 [73]—are not necessarily considered specialty or complex alloys. It is to say that more steel can also be a solution, as long as it is used when and where necessary to support servitization and, further along, sustainability.

DISCUSSIONS AND CONCLUSIONS

This article used the criteria of sustainable urban metabolism and of circles of sustainability to analyze the contributions that three different case studies of servitization could provide to sustainable cities. Furthermore, the presence, contribution, and challenges regarding the steel within their servitization initiatives was evaluated.

Table 7 summarizes the results and discussions derived from analysis and evaluation, and serves to reinforce how useful all servitization case studies were towards improving eco-efficiency, resilience, sustainability, and self-sufficiency in the cities they were, or would be, deployed. All three case studies helped (a) lower dependency on external energy inputs, and (b) lower the output of emissions; even if at the expense of increasing local material stocks.

In the case of energy, deploying photovoltaic solar panels onto the roofs of houses significantly changed how energy is produced and consumed. When analyzing the case of housing, creating gardens and switching to eco-efficient appliances had substantial positive impact on health, wellbeing, and waste generation. Additionally, on what concerned mobility, a combined set of social and infrastructural measures has been proven capable of not only considerably reducing emissions, but also of stimulating job creation.

Table 7. Summary of results and discussions.

Case Study	Main Servitization Contributions According To		Steel's		
	Sustainable Urban Metabolism	Circles of Sustainability	Presence	Contribution	Challenge
Energy	• Lower external energy inputs; • Increased energy circularity and flow within boundaries;	• Materials and Energy; • Water and Air; • Emissions and Waste;	Decreased	Less steel in the right places can help create more environmental value.	HOW MUCH steel to use, WHERE to use steel.

	• Higher material stocks within boundaries; • Lower emissions outputs.	• Production and Sourcing; • Consumption and Use.			
Housing	• Lower inputs overall; • Higher stocks and flows of food and materials within boundaries; • Lower emissions outputs.	• Constructions and Settlement; • Water and Air; • Materials and Energy; • Emissions and Waste; • Health and Wellbeing; • Consumption and Use.	Steady	Different alloys used to the best of their potential can support other goods' and services' environmental values.	WHAT type of steel to use, HOW to use steel optimally.
Mobility	• Higher materials inputs; • Lower external energy inputs; • Higher materials stocks; • Reduced material flows; • Lower emissions outputs.	• Water and Air; • Emissions and Waste; • Labor and Welfare; • Wealth and Distribution; • Health and Wellbeing.	Increased	Regardless of quantity, optimal applications of even the simplest of steel alloys can help improve the environmental values of a service or good.	WHEN and WHERE to use steel.

When evaluating steel's behavior, each case study provided a unique insight. In the first case, steel's presence decreased, but its contribution to electricity generation and emission reduction was improved. In the second case, steel's presence was virtually unaltered, but the way it was used highlighted the potential for supporting a servitization initiative's environmental values. And in the third case, steel's presence increased only where and when it was more capable of contributing to the environmental goals at hand, even to the point of compensating increased energy consumption for its production.

These differences bring to light the importance that steelmakers also pay close attention to service-providing projects involving their clients and their products, since it was noticed that servitization is capable of altering steel demand in terms of quantity, but also quality and specialization requirements. The effects of servitization on the demand-side can change supply-side dynamics as well, creating both challenges and opportunities for steelmakers.

Steel has a structural role in solar panels, as opposed to a direct operational one as in hydropower plants, this not only changes how much steel is necessary but where it is used, potentially requiring a steelmaker to consider migrating to new and upcoming markets. When it comes to eco-efficient appliances, specialized types of alloys and how they help the product improve efficiency play a bigger role than quantity, a situation in which close collaboration with a client's development cycle might favor the steelmaker as well. Furthermore, directing more production and technology development efforts towards steel alloys that supply manufacturers and assemblers of vehicles, which have characteristics that favor environmental values, can pose as an opportunity for portfolio expansion and market share capture. Furthermore, all of these results would contribute even more to the overall environmental performance of the global steel industry, and for it to support the achievement of SDG goals if associated with a transition toward fossil-free production processes.

When addressing services, notably those with environmental purposes, most research as of the publication of this article focus on the operation, feasibility, and impacts of the proposed solution, and not on the holistic and systemic effects that feed back to the supply-side of the materials they replace, reduce, or displace. In addition, although different tools can be used to analyze and evaluate the benefits that servitization can provide to a sustainable city, more research is needed on the effects that servitization and other service-providing practices have on the commodities that flow through and within a city as a consequence of their implementation.

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CHAPTER 3. CRITICAL REVIEW OF EXISTING METHODOLOGICAL TOOLS

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Analyzing Symbiotic Relationships in Sustainable Cities - A framework

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The development of green, ecological cities or eco-cities has been introduced as a mean to support sustainable urban development within a social, economic, environmental, and demographic context (Tsolakis, Anthopoulos, 2015). The Eco-city concept was introduced by Urban Ecology, a non-profit organization founded in 1975 by Richard Register (Roseland, 1997). An Eco-city ensures the well-being of its citizens via a holistic urban planning and management approach with the aim of eliminating waste and emissions (Register, 1987). From a systemic point of view, an eco-city can be described as a set of different complex subsystems, which need to be associated or reconnected in order to deliver the desired outcomes (Diemer, Morales, 2016).

In the 1990s, the term "sustainable city" replaced that of "ecological city" in response to the creation of the ICLEI in 1990, the European Green Book on Urban Environment (1990) and the Rio Conference (1992). The ICLEI was established at the *World Congress of Local Governments for a Sustainable Future,* at the United Nations in New York. Its mission was to build and serve a worldwide movement of local governments to achieve tangible improvements in global sustainability; with a special focus on improving environmental conditions through cumulative local actions, (200 local governments from 43 countries were involved). The European Commission Green Book on the Urban Environment was published in June 1990.Chapter 1 focused on the future of the urban environment; Chapter 2 was titled « Towards a Community Strategy for the Urban Environment ». Dealing with the problems of the urban environment, the report addressed not just the proximate causes of environmental degradation but examined "the social and economic choices? Which are the real roots of the problems » (1990, p. 1). Chapter 7: « Promoting Sustainable Human Settlement Development » of the Agenda 21, states that « individual cities should participate in international city network to exchange experiences and mobilize national and international technical and financial support».

Emelianoff and Theys (2001) argue that the sustainable city operates a triple fracture in contrast to the ecological city: (1) Environmental concerns are no longer separated from the urban projects of economic, social, or cultural policies of cities. (2) The willingness to evaluate the consequences of urban development at a global scale or in a very long term. (3) The city becomes a human and social environment, and not an anti-urban ecological vision. In fact, sustainable cities face the same major challenges as urban population growth in developing countries (migrations, movements from rural areas, births); aging populations in developed countries (aging populations will interact with younger populations); environmental changes including climate, vulnerability to infectious diseases, limitations in resources such as water, energy and food. In fact, sustainable cities face the same major challenges as developing or developed countries do; urban population growth (migration, movement from rural areas, birth rate), aging populations (aging populations' interaction with younger populations), environmental changes that include climate, vulnerability to infectious diseases, limitations in the availability of resources such as water, energy, and food. When a city outgrows political boundaries, its government loses the capacity to solve the problems residents face; governance starts to be shared between new entities and the civil society needs to be more involved.

Such challenges explain why the European Commission has recently increased its focus on urban issues and sustainable cities, as a response to the fact that by 2020, it is estimated that almost 80% of EU citizens will be living in cities. The overall objective is to enhance the sustainability of EU cities to achieve, by 2050, that all Europeans are "*living well, within the limits of the planet*".

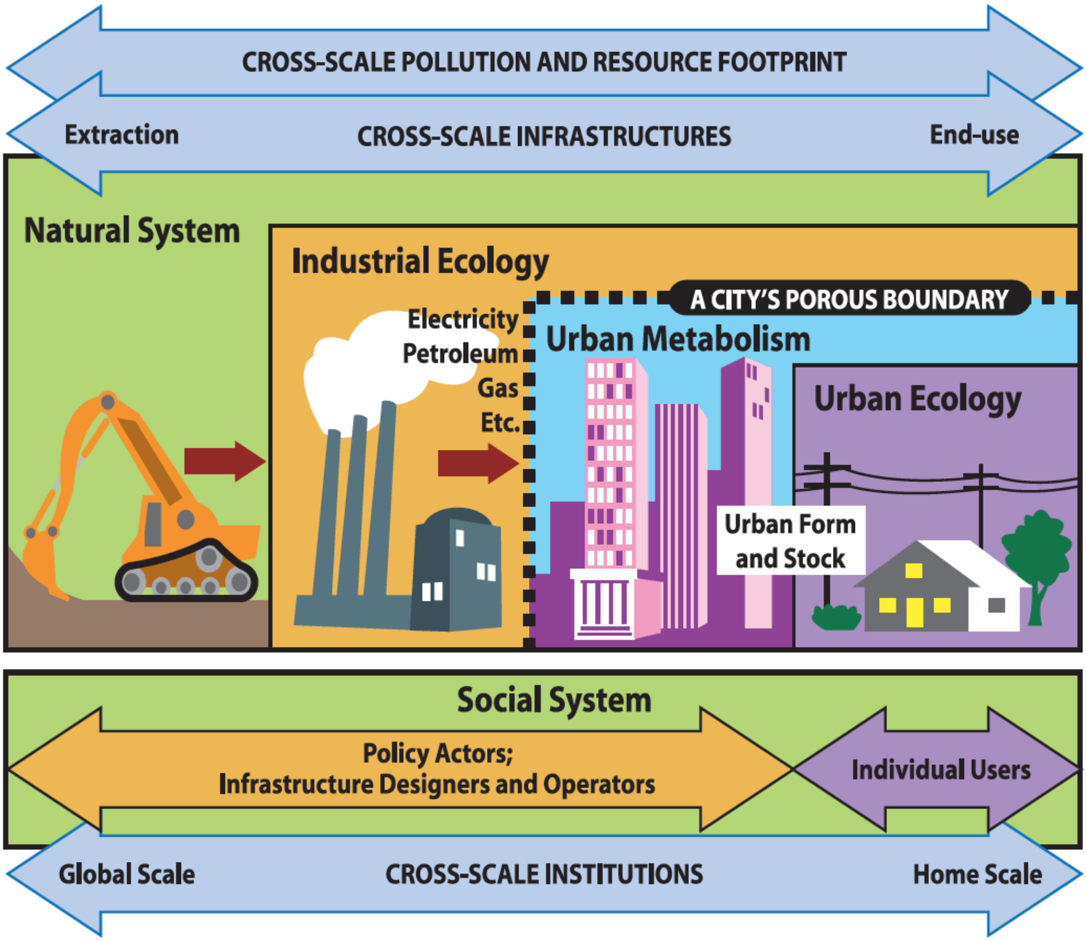
This paper proposes different investigations to understand how a city becomes a sustainable city. We present the following hypothesis: a city becomes more and more sustainable as long as it is able to develop and improve symbiotic relationships. By nature, symbiotic is defined as any relationship between individuals of different species where both individuals benefit. Therefore, a symbiotic city has "*mutually beneficial relationships with its macro and micro ecosystems. It produces ecosystem services that are equal or greater than its net use of those services. The transition to a symbiotic city requires a cultural and economic recognition that we are embedded in and dependent upon our ecosystems. A symbiotic city enhances the natural environment, sustainable economic activity and quality of life*" (2012, Future Proofing Cities Working Group, July, 2012). To challenge that idea, we should start by understanding the complexity of symbiotic relationships in an interdisciplinary perspective. Then, we propose methods and materials (System Dynamics, Material Flow Analysis, circles of sustainability) to improve our model. Finally, we present a few examples of European sustainable cities and discuss the challenges and prospects of such social innovation.

FROM DIFFERENT ECOLOGIES PERSPECTIVES TO SYMBIOSIS: AN INTERDISCIPLINARY APPROACH

It is relevant for the society to understand the complexity of the symbiosis in an interdisciplinary perspective (Ramaswani, Weible, Alii, 2012) to get a broader understanding of ecosystems (natural or manmade) and recognize why the symbiotic relationship is advantageous in comparison with other different categories available in an ecosystem (competitive, neutral, or collaborative) to seek for prospective sustainable objectives.

Over the past three decades, cities have made a revolution by searching to become more sustainable and to reduce their ecological footprint (Rees, 1992). It was urgent to reduce pollution, organize urbanization, propose future transports, preserve scarce resources, and take account of the consequences of climate change. This revolution is ecological and social (Rasmawami, Chavez, Chertow, 2012). It is to present a broad vision of sustainability (social-ecological-infrastructure systems) that takes into account the industrial character of modern societies, the social impact of development, the strength of multiculturalism, and the need for a genuine political will for change (Figure 20).

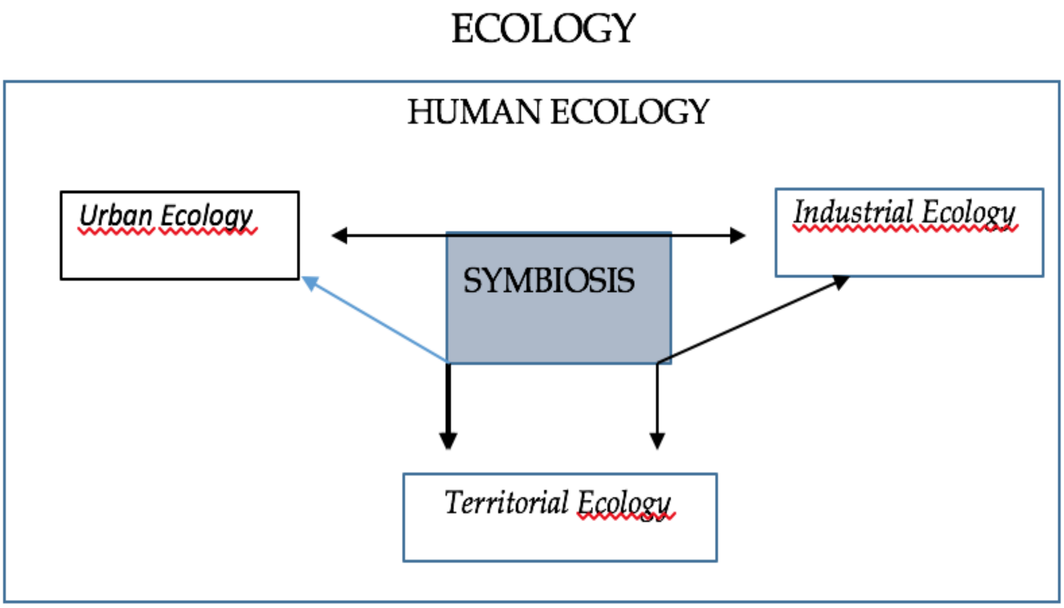
Figure 20. Illustration of Socio-ecological-infrastructural systems



Source: Ramaswami (2012, p. 803)

In what follows, we propose to analyze symbiotic relationships in the cities in a framework that use the following key entrances (Figure 21): industrial ecology, urban ecology, and territorial ecology.

Figure 21. Different framework on human ecosystem symbiosis



Source : Ribeyre, Gombert-Courvoisier, Sennes (2015) modified

Industrial Ecology

Industrial Ecology came up as a combination of an academic and business idea (Chertow, 2007), arguing that environmental constraints require new ways of thinking about industrial production (Frosch, Gallopoulos, 1989) and highlighting the need to "mimic", in their production facilities, the operation of ecosystems in nature that generate no waste because of intricate channels for reusing residues (Duchina, Hertwich, 2003). According to Ehrenfeld (2000, 2010), natural ecosystems offer the only worldly example available to humans long-lived, robust, resilient living system, the characteristic of which are fall features of the radical idea of sustainability. Our own human history offers no similar source for pragmatically distinct thinking. Three collective features of stable ecosystems appear very important: connectedness, community and cooperation.

Industrial Ecology is relevant to the social structure, on one hand, taken as an interdisciplinary approach linking hard, social, and applied sciences as an example of its relevant contribution to identify the drivers of a strong sustainable development model in the industrial ecosystem (Diemer, Labrune, 2007). In a previous article, we associated strong sustainability with four pillars of industrial symbiosis: Eco-efficiency, resilience, cooperation, and proximity (Diemer, Morales, 2016a). The technology paradigm change seems to be the key driver needed for a transition from the current industrial system to a sustainable socioeconomic reality, where the industrial system can thrive. This change in the technology paradigm should highlight the relevance of a social dimension of studies related with the geographers' approach to the territorial ecology perspective (Buclet, 2011). The identification of collaborative synergies between stakeholders is presented as a way of launching the social cooperation in the industrial ecosystem, something that helps us understand the limits of the technology. In this sense, Industrial Ecology attempts to reduce the idealization of technology, turning on the social relevance of the actor's geographic proximity, flow's optimization, collaborative and resilience interests and motivations, therefore, providing a key role to the local authorities (Diemer, Figuiere & Pradel, 2013).

To identify the field of Industrial Ecology it is necessary to understand the study case of industrial symbiosis at Kalundborg, Denmark (Knight, 1990, Barnes, 1992). Traditionally, industrial symbiosis separates industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or by-products (Chertow, 2000). Symbiotic relationships were defined because of the low availability of groundwater and the need for a surface water source which, once identified, became a key part of the resource exchange network there (Chertow, 2007).

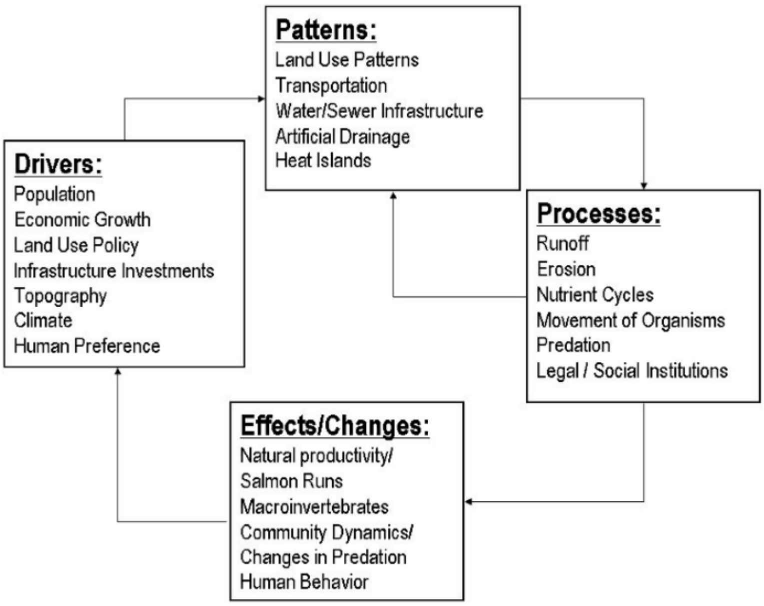
It is fundamental that "dedicated systems integrators" work as bridges for the success of the industrial ecology. These bridges could be from two natures: social (actors with an active role, or technical skills and knowhow). (Vernay, Mulder, 2015)

Urban Ecology

Urban ecology is the study of ecosystems that include humans living in cities and urbanizing landscapes (Rebele, 1994). This last one refers to environments dominated by high residential density and commercial buildings, paved surfaces, and other urban-related factors that create a unique landscape dissimilar to most previously studied environments in the field of ecology (Mcintyre, Knowlees-Yanez, Hope, 2000). Urban ecology is an interdisciplinary field that aims to understand how human beings and ecological processes can coexist in human-dominated systems, and helps societies with their efforts to become more sustainable. Urban ecology has deep roots in many disciplines including anthropology, climatology, ecology, economics, engineering, geography, landscape architecture, sociology, urban planning… This is why Marzluff and al. (2000) proposed three definitions of urban ecology as a field (Figure 22):

(1) Ecology and evolution of organisms that happen to live within city boundaries; (2) Biological, political, economic, and cultural ecology of Homo Sapiens in urban settings; (3) Cities as emergent phenomena of coupled human and natural processes with implications for evolution and survival of our own and other species. That third view is associated to our research and allows "*various aspects of the human enterprise and nature to be seen as interacting forces that shape measurable patterns and processes*" (Marzluff and al., 2000). Thus, some key drivers cause patterns, and processes themselves, affect the interactions between human and natural drivers by their effects and changes to the urban ecosystem.

Figure 22. Urban ecology, interactive forces between humans and nature



Source: Marzluff and al. (2000)

The final objective of this field is the understanding of the human interactions and behaviors to fulfill the human needs and improve the quality of their life in an urban environment considering the physical boundaries (Sukopp, 2000). To clarify this objective, it is important to remember that, income and yield are not the only motivation of the social system construction of a social system, some factors as work, leisure, accommodation and mobility, are also exceeded. In order to discuss about quality of life and livability, it is important to include concepts as creativity, awareness, security, assessment, association, and individual challenges that are important for every citizen in the city.

Urban ecology attempts to depict the social system structure of cities through an historical perspective to find optimal structures for the fulfillment of social, human, biological, and ecological needs. From interdisciplinary and system dynamics, it proposes better solutions to specific and located problems, considering the producers' and consumers' perspective, at global and local scales (Ribeyre, Gombert-Courvoisier & Sennes, 2015).

Developing symbiosis between urban infrastructures implies that the operators of the infrastructures can align their interests (Mulder, 2016). Urban symbiosis is not a *"novelty conquering the world, but a rearrangement of actors in a specific local context"* (Vernay, Mulder, 2015).

Agreements between urban ecology, industrial ecology, family ecology, and territorial ecology at a micro level, are relevant for a better understanding of the social limits. Furthermore, they help stakeholders to share responsibilities in the process. While the micro level is comprised of physical balances for a growing number of materials and spatial units, the macro level is concerned with the formulation and evaluation of taken choices by decision makers. As in many other fields, there are substantial challenges in achieving conceptual and operational linkages between micro and macro levels. An attempt to bridge this gap takes the form of an intermediate (or meso) level of analysis represented by the Industrial symbiosis.

Territorial Ecology

It is difficult to separate territorial ecology from urban ecology and industrial ecology. The former is coined from the latter two, specifically the methodology of analyzing the metabolism of a territory. Human societies define their territories interacting with their environment and other people in it. A territory is well thought of as "*a system of socio-ecological interactions*" (Buclet, 2015). Material and immaterial flows are circulating within a territorial system. The socio-ecological interactions linked to the territorial system, appear as a dynamic interaction between self-organizing subsystems: the resource system, the user, the governance system, and the infrastructure system. At the same time, territorial ecology cannot be reduced to a spatial dimension; proximity focuses on the various forms of the relationship between the actors within the process of building a territory (organizational proximity and institutional proximity).

Territorial ecology based on analysis of territorial metabolism. The material flows analysis method applied to a territorial scale (Madelrieux, Buclet, Lescoat, Moraine, 2017). A European network has been created around two methodological guides. The principle addresses the fact that the flows come within this determined socio-ecological system and can be stored and/or pushed out, depending on the human activities which arise and communicate functional needs. These flows are mainly material flows: biomass, fossil fuels, minerals, metals, construction equipment, etc.

Table 8. Flows quantification

1 / Inputs

• Local drivers:

- Local extraction (used) materials, including oxygen consumed by combustion,

- Unused local extraction,

• Imports (from other regions and countries): raw materials, fuel, finished or semi-finished,

• Indirect flows associated with imports: samples taken outside to allow imports (equivalent raw materials and unused extracted imported products);

2 / Outputs:

• Materials returned to the nature:

- Air emissions (including water produced by combustion) and water, landfilled,

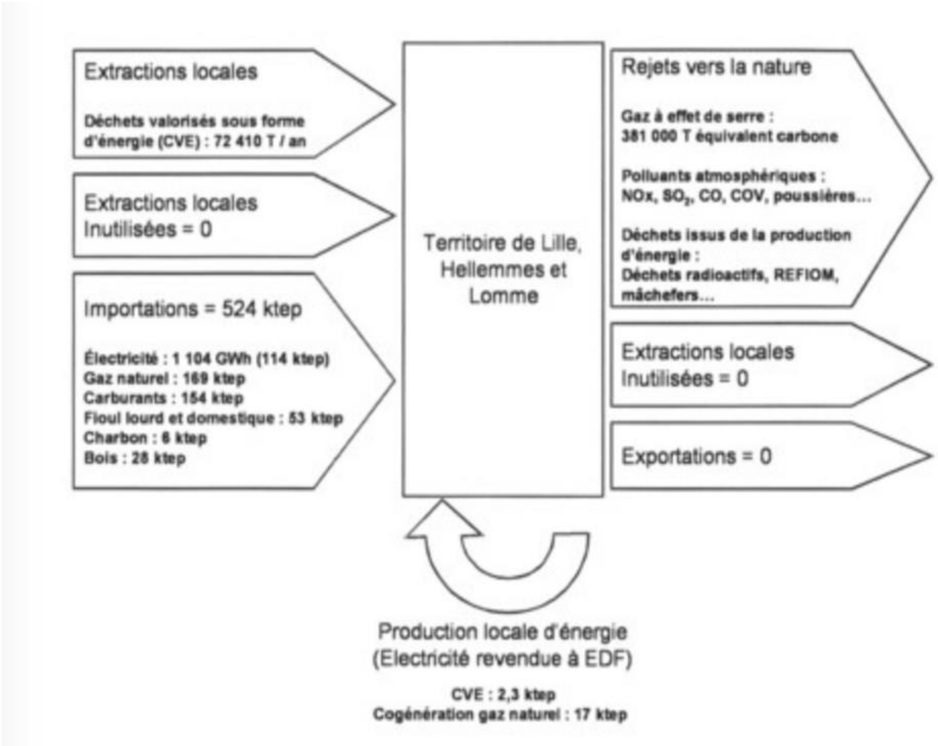
- Purpose and dissipative losses,

• Unused local extraction,

• Exports (to other regions or countries): raw materials, fuel, finished or semi-finished products, waste,

• Indirect flows associated with exports: samples taken to allow exports (equivalent raw materials and unused extraction of exported products).

Figure 23. Energy accounting, City of Lille (France)



Source : Duret, Mat, Bonard, Dastrevigne, Lafragette (2007, p. 76)

Works on the territorial metabolism make it possible to understand the first material flows image mobilized by a system at the macro level (type of flow, volume, structure) and therefore to characterize a territory according to these flows. The area and supply chain distances method is about defining the optimal areas from which some flows (energy, food, water) for a territory should be supplied. This method aims to characterize and measure the interdependence of a group of linked territories, and identify the supply chains of a given area.

The territorial approach invites us to consider the two essential dimensions of the implementation of an industrial ecology approach conceived as a collective action (Beaurain, Brullot, 2011): (i) the dissemination among the actors of a set of common values which constitute the necessary conditions for coordinating actors, in the form of constraint and potential; (ii) the increase in interactions between firms, and between them and other actors in the territory, reflecting the existence of collective action. These two dimensions raise the question of the nature of the project of shared territory and the mode of coordination between the actors. Thus, proximity may introduce a new corpus to industrial ecology. Hence, Nicolas

Buclet prefers to use the term "industrial and territorial ecology" and become a new pillar of the strong sustainability.

IDENTIFIED URBAN SYMBIOSIS METHODOLOGIES

Assessment of sustainable cities involves combining the result of several approaches to research. In what follows, we will refer to three approaches: (1) system dynamics developed in the 60's by J.J Forrester (urban dynamics); (2) the sustainable urban metabolism perceived as an ecosystem (mainly material and energy flow analysis and input-output assessments), and (3) the circles of sustainability from James (2015).

From System Dynamics to Urban Dynamics

Since the publication of Industrial Dynamics (Forrester, 1961), Urban Dynamics (Forrester, 1969), World Dynamics (Forrester, 1971) and The Limits to Growth (Meadows, 1972), there has been a long tradition of using system dynamics to study public management questions. System dynamics models cover a range of areas in public affairs including public health (Thomson, 2007, 2008), energy and environment (Sterman, 2008), social welfare (Zagonel, 2004), sustainable development (Mashayekhi, 1998), education (Andersen, 1990), security (Weaver and Richardson, 2006) and many others related areas. System dynamics is a form of computer simulation modeling, which uses the concepts of information feedback and state variables to model social systems and to explore the link between system structure and time-evolutionary behavior (Forrester, 1968). To model the dynamic behavior of a system, Forrester (1969, p. 12) proposes reorganizing four hierarchies of structure: (1) closed boundary around the system; (2) feedback loops as the basic structural elements within the boundary; (3) level (state) variables representing accumulations within the feedback loops; (4) rate (flow) variables representing activity within the feedback loops.

Closed System boundary: To develop a complete concept of a system, the boundary must be established within the system interactions that give the system its characteristic behavior. Forrester states that "the closed boundary does not mean that the system is unaffected by outside occurrences. But it does say that those outside occurrences can be viewed as random happenings that impinge on the system and do not themselves give the system its intrinsic growth and stability characteristics" (ibid).

Feedback loop structure: The dynamic behavior of systems is generated within feedback loops. A feedback loop is composed of two kinds of variables, called rate and level variables. A feedback loop is a structure[15] within which a decision point – the rate equation – controls a flow or action stream. The action is integrated to generate a system level. Information about the level is the basis on which the flow rate is controlled.

The aim of system dynamics modelling is to explain behavior by providing a causal theory, and then to use that theory as the basis for designing intervention policies into the system's structure, which then attempts to change the subsequent behavior and improve performance (Lane, 2008). Each system dynamics study starts with a problematic situation and the set of assumptions that is used to describe the problematic situation. These assumptions are taken to be held in a MMDS.

Each causal link in a model has a polarity, the direction of effect that the influencing variable has on the influenced variable. The nature of that influence depends on the type of causal link being considered. In a system dynamics model the polarity of each feedback loop is a crucial part of understanding the model behavior. The perturbation of a loop may result in the magnification of the original effect; this unstable response is known as a positive feedback loop polarity. Alternatively, a perturbation may be counter-acted, or resisted by the operation of the loop. This equilibrating response is known as a negative feedback loop polarity.

- *Role of simulation:* the interaction of these complicated relationships is almost always beyond the capability of the human mind to infer, as mental simulation is deficient. Computer simulation is therefore rigorously needed to deduce the consequences of these relationships and to reveal the counter-intuitive behavior that results from the assumptions in the model.

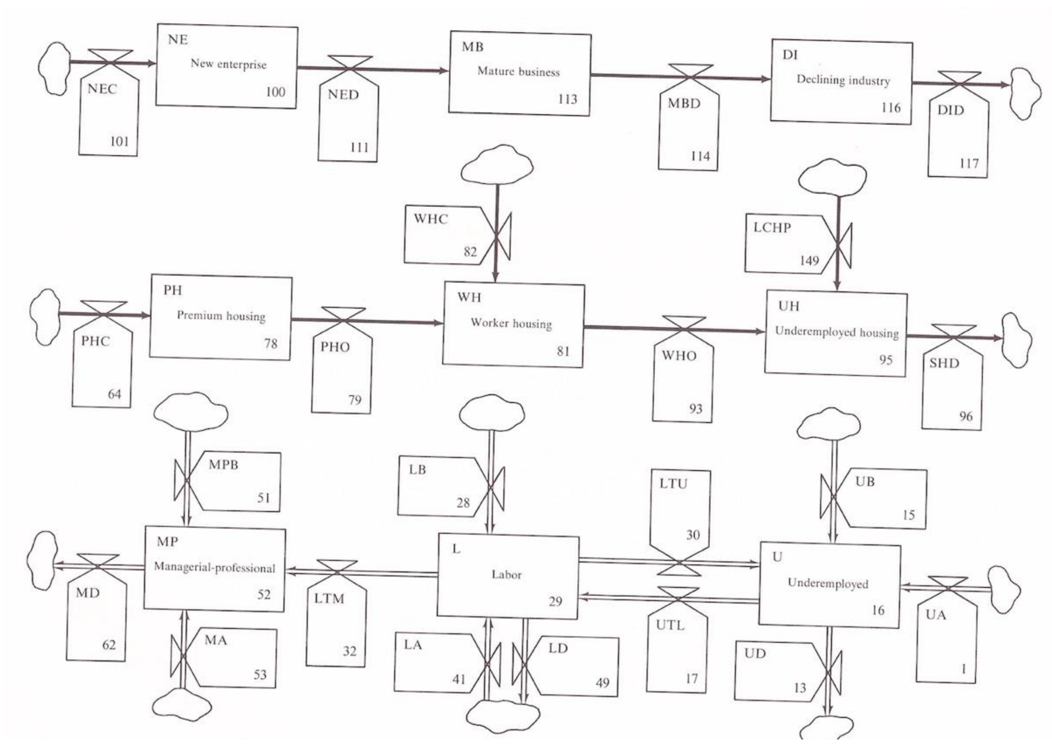
- *Diagramming methods*: Two diagramming methods are dominant in the system dynamics community. Broad Representations of the variables and the feedback

[15] "*The most important concept in establishing the structure of a system is the idea that all actions take place within feedback loops. The feedback loop is the closed path that connect an action to its effect on the surrounding conditions, and these resulting conditions in turn come back as "information" to influence further action. We often erroneously think of cause and effect as flowing in only one direction. We speak of action A causing result B. But such a perception is incomplete. Result B represents a new condition of the system that changes the future influences that affect action at A*" (1971, p. 17).

structure of a model are conveyed using CLD. In contrast SFD is more detailed, discriminating both state and flow variables.

In *Urban dynamics*, Forrester (1969) presents a computer simulation model of how a city first grows, then stagnates, and finally decays (Figure 24). The model[16] contains the major components of the city: three classes of population (the under-employed, labor, and management), three types of housing (one for each of the population classes) and three types of industry (new, mature, and declining). One or more of the 22 rate variables, which are functions of behavior characteristics, exogenously set policies, and the drivers, control the changes over time of each of these drivers. This is what produces people's perception of a city.

Figure 24. Structure of urban model



Source: Forrester (1969, p. 16)

[16] In fact, there are two models. One, a growth model, generates the life cycle of an urban area from its founding through growth to its arrival at a state of stagnation and decay after a period of 250 years. The other one, begins with the resulting depressed conditions and is used to examine how various policies would alter the conditions of the urban area over the next 50 years.

Urban Dynamics shows how urban problems such as housing shortages or unemployment are generated by internal forces and cannot be solved by attacking external symptoms. Forrester's main endeavor is the development of a tool to be used by urban policy makers.

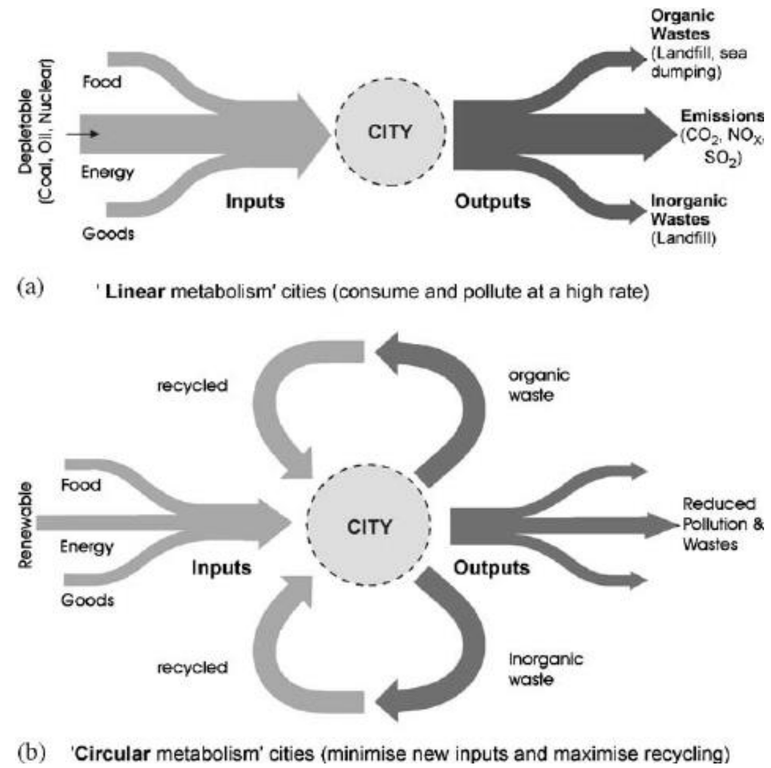
Material and Energy Flow Analysis

One of the underlying principles in Urban Metabolism is the mass conservation finding ways in which to transform industrial activity from what is largely a non-sustainable system into a system that resembles more and more closely a sustainable one. MEFA is the study of material and energy accounting by identifying and quantifying material and energy usages and assessing their impacts on the environment. It also aims to implement opportunities to effect environmental improvements (Graedel & Allenby, 1995). The material and energy flows (Figure 25): inputs and outputs of a city or territory are the basic features for establishing a material flow balance. Thus, it is necessary to identify the stocks and the potential advantages from its operation. This metabolic level support takes into account "the required and harmful" consumption (the inevitable household expenditure) such as heat, electricity, and food, considering that there is a correlation between needs and resources to develop the local production of these products, with the corresponding benefits in terms of local economy, employment, greenhouse gas reduction, etc. The metabolism process will shift gradually to zero waste, positive energy, and a closed water cycle.

The first and most important output of MEFA methodology is without doubt (1) the global and interconnected dimension it puts forward the urban ecosystems theory, supplying relevant data, that could be qualitative and quantitative to the decision-making process at economic and political level. Secondly, (2) the contribution made to the input-output theory including the global analysis of other sub-systems that are out of the main system but are closely linked with the system's activity working out as suppliers or consumers. The third feature (3) is radical understanding as an alternative revolution of the broadly developed social productive system, that looks for improved efficiency in the social systems based on an alternative socio-economic framework able to drive the market structure far across the restricted technological based solutions.

Urban Ecology is achieving a strong sustainable approach, challenging us to think about the structures' evolution in the cities. This evolution is figured out considering relevant insights as different organization patterns that are not necessarily new. If we look backwards in history at the collaborative/cooperative social structures, for example, the kind of structures used in the past, but adapted in a current social system structure, could help to make the bridge in between the long-term political goals and the short-term profits (Metereau & Figuière, 2015).

Figure 25. The metabolism of cities towards metabolism



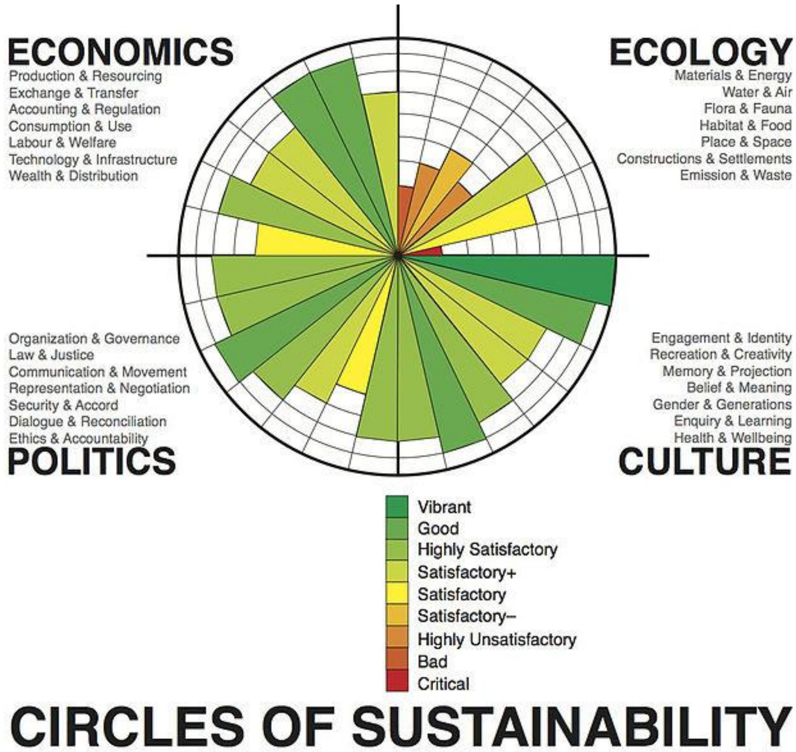
Source: Doughty & Hammond, 2004 (adapted from Girardet [3,4] and Rogers [6])

Circles of sustainability approach

The *Circles of Sustainability* approach proposes a "*redefinition of sustainability, intersecting "with other social conditions, such as resilience, livability, adaptation, innovation and reconciliation as basic conditions of positive social life*" (James, 2015, p. XIV). This approach takes the positive intention of the "three pillars" phrase and, for the first time, locates that well-intentioned spirit in an integrated and generalizing. The Circles of Sustainability are intended to be flexible, modular and systematic (Figure 26). The *Circles of Sustainability* approach provides a relatively simple view of the sustainability of a particular city, urban settlement, or region. The circular figure is divided into four domains: ecology, economics, politics, and culture. Each of these domains is divided into seven subdomains, with the names of each of these listed from top to bottom under each domain name. Assessment is conducted on a nine-point scale. The scale ranges from the first step: "critical sustainability", to the ninth step: "vibrant sustainability".

When the figure is presented in color, it is based on a traffic-light color scheme with critical sustainability marked in red and vibrant sustainability marked in green. The center step, basic sustainability, is colored in amber – with other steps ranging between amber and red, or amber and green. If printed in black and white, the grey-scale used here is intended to simulate the color range.

Figure 26. Guideline Circles of Sustainability



Source: James (2015)

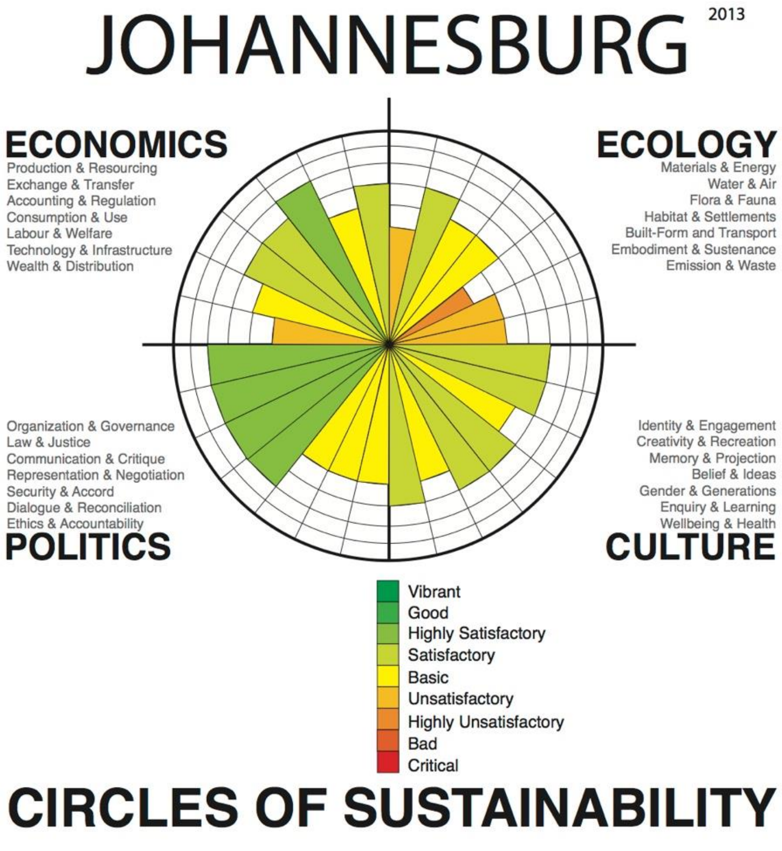
Each part of the approach has been developed so that it operates as part of a toolbox for understanding different urban areas. More than an answer of specific issues, the Circles of Sustainability method needs to be considered in response to some fundamental social issues (wealth distribution in the city).

Sustainable cities – A few examples

Many studies consider one methodology as a framework. A relevant example is "*The Energy consumers & suppliers model in Paris*" (Kim, 2015) that produces available data about the energy consumption pattern, the amount and trajectory of input and output natural resources output flux. This MEFA assessment in a city is clear evidence that cities can be thought as urban systems, and assessed with dynamic, multiscale, and interconnected tools. At the same time, several cities are going beyond analysis of urban metabolism and developing different types of environmental footprints that integrate in-boundary and trans-boundaries water use, energy use, and greenhouse gases (GHGs) associated with production and consumption activities (Kennedy, Baker, Dhakal, Ramaswami, 2012).

Another good example is related to the Circles of Sustainability model. Figure 27 shows the Circles of Sustainability profile of Johannesburg, a city that began its massive development under the oppressive system of apartheid.

Figure 27. Johannesburg Circles of Sustainability



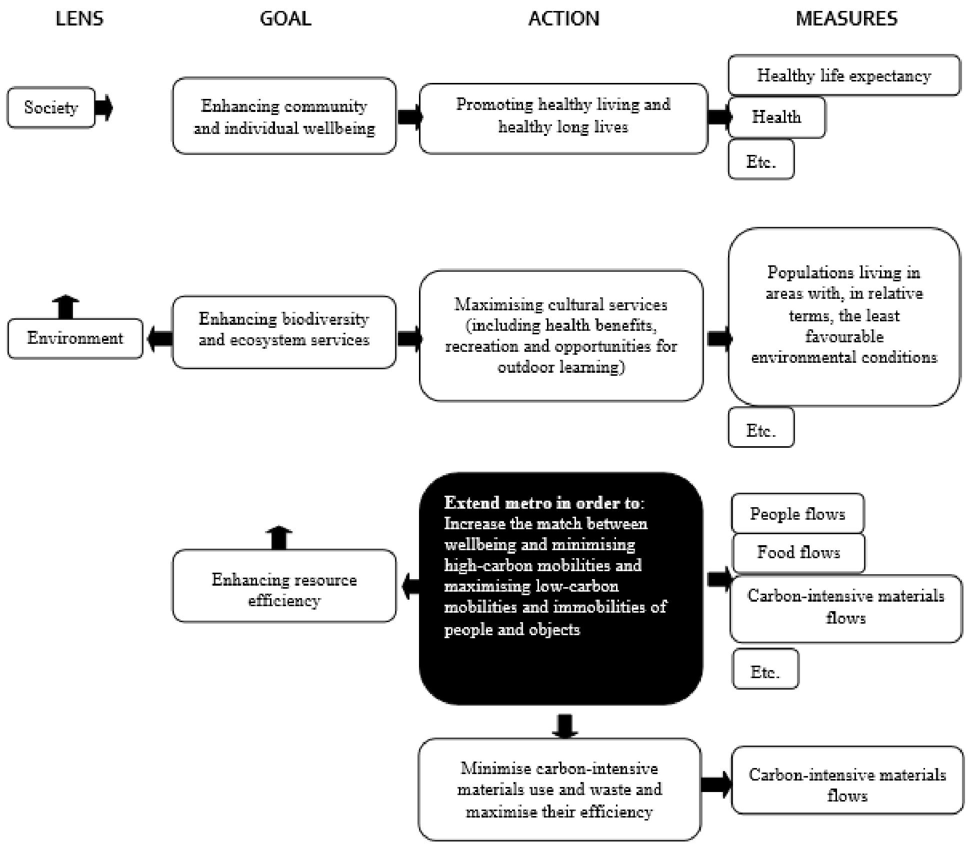
Source: James (2015)

In 1975, Ponte City, a cylindrical skyscraper was built in the "whites' only area" of Hillbrow, making it the highest residential tower in Africa. In the same year, a freeway was complete connecting the south, including Soweto, to the city center; and extending to Sandton, the wealthy northern commercial center of Johannesburg. All of these infrastructure developments became barriers of the post-apartheid spatial heritage of the city. Service jobs connected the poor south-west area and the wealthy north region. These jobs were available to those in the south who could bear the heavy peak travel times between the north and the south. Today, long after the end of formal separate development, the prior configuration of stark spatial racial separation continues to confront the city. There are no walls dividing people, but the effect is no less tangible. This is the dual reality of the city. It is a metropolis with one of the highest levels of inequality in the world. Recently, Johannesburg has launched a 'Growth and Development Strategy' with a long-term vision for 2040 to make "Johannesburg a world-class African city of the future — a vibrant, economically inclusive and multi-cultural African city; a city that provides real quality of life for all its citizens".

Urban methodology examples applied to sustainable cities

In order to move towards increased sustainability and livability, it is important first to understand how cities function and how well they perform. The CAM is an urban analysis framework for holistically measuring the performance of a city, demonstrating the need and defining the parameters for the design of city interventions (Figure 28). It is important to reiterate that the CAM is built upon international academic and practitioner literature and is practice-refined specifically for the UK (Leach et al., 2016).

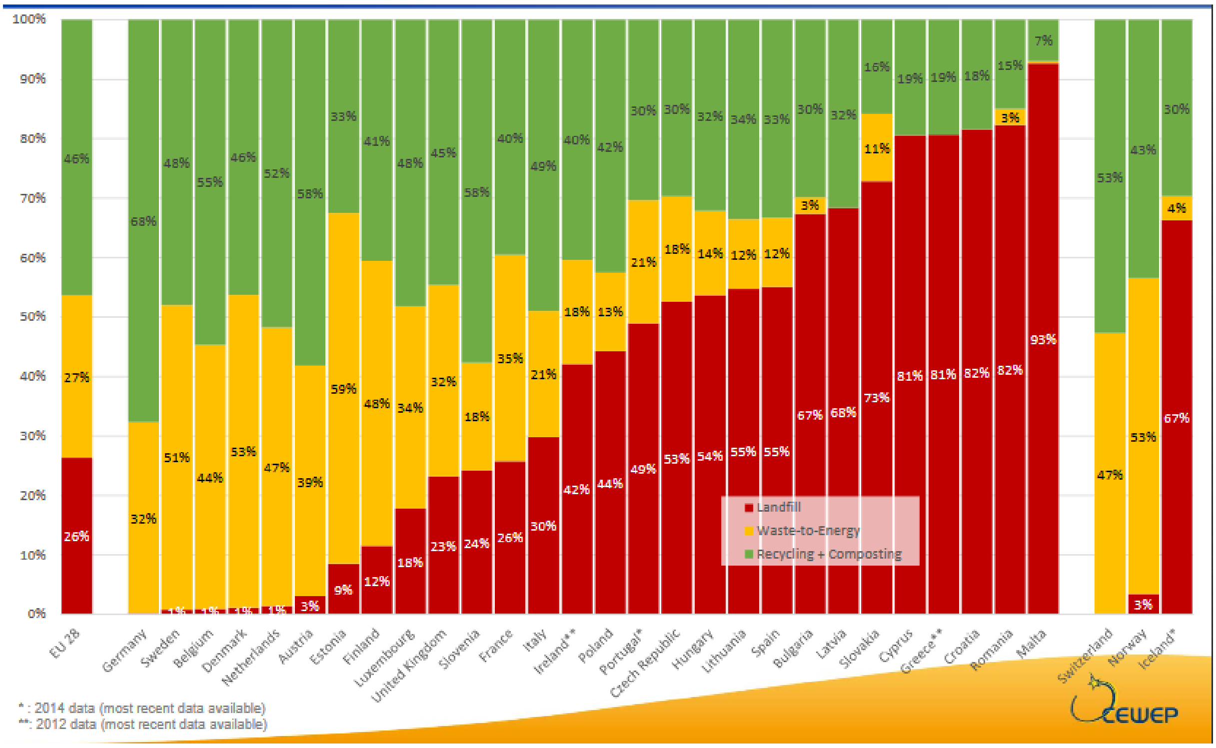
Figure 28. Interdependencies at CAM



Source: Leach et al. (2016)

Energy recovery from wastes is also an important option that should be expanded, together with material recycling and biological treatment, to support the efforts in other cities to increase sustainability. The European cities that are the best urban places to live in have included waste-to-energy as one very significant method for their sustainable way of managing their wastes (Figure 29). All EU reports show that the countries that present the highest recycling rates are the ones that have significant part or their waste incinerated with energy recovery. The following European cities have been selected among the most sustainable: Vienna, Munich, Berlin, Greater Copenhagen, Malmo, Zurich, Amsterdam, Brescia, Barcelona, Mallorca; all of these cities are recognized as the ones with the most sustainable use of energy recovery from wastes, and this is considered to be a major parameter of their achievements (Chaliki, P., Psomopoulos, C.S., Themelis, N. J., 2016).

Figure 29. Waste treatment in 2015, EU 28 + Switzerland, Norway and Iceland



Source: CEWEP, 2017.

In the last years, these cities remain among the best places to live in every ranking, or they have been included in the lists of the most sustainable cities in the world. They have reduced their carbon footprint (Ramaswami, Chavez, Chertow, 2012); they have been leaders in adopting the most advanced and sustainable solutions to improve their citizens' lives and continue to do so (Chaliki, P., Psomopoulos, C.S., Themelis, N. J., 2016). Thus, the awareness of environmental quality can be regarded as a civic value and a way to induce proactive policies leading to the implementation of alternative systems of consumption and production (Mega, 1996).

DISCUSSION

As a matter of fact, it is the economic, social, and environmental dimensions, all of them interconnected in a system dynamic approach, which could lead the Industrial Ecology to dig deep in the ideological structures. The understanding and sharing of the ideological structures could reconnect sub-ecosystems at sustainable cities: considering symbiosis as one key of a sustainable urban ecosystem and building a new sustainable development model. Represented for example in a revolutionary mindset at the business sector. At the same time, social understanding will drive the society to use a shared language, which might be impossible without exploring the relevance of the political, cultural, ecological, and economic dimensions (Metereau & Figuière, 2015).

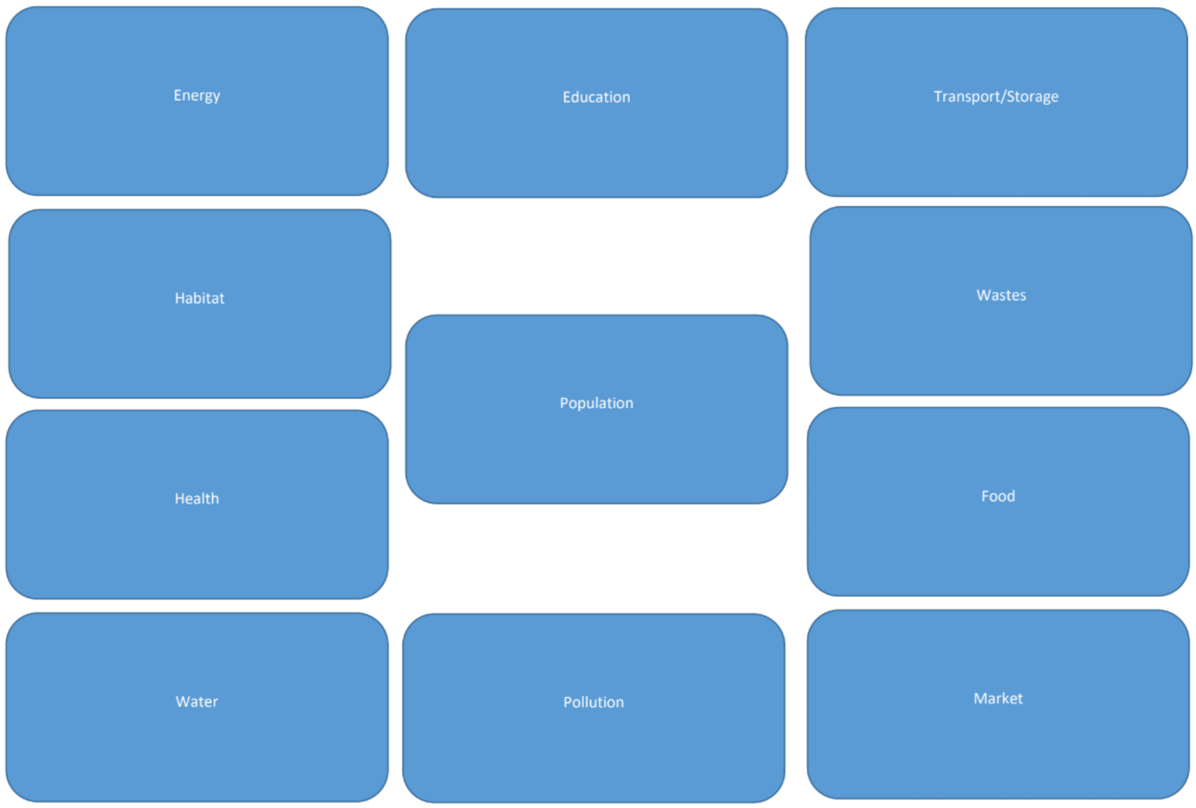
Table 9 shows that symbiotic relationship is advantageous in comparison with other different categories in a multidimensional perspective of an urban ecosystem. It generates: (1) the smallest ecological footprint, waste to energy conversion, and the lowest quantity of pollution in the environmental dimension; (2) Land efficiency and blooming employment conditions in the social dimension; and finally, (3) Thriving flow material and energy mobility, decreasing the quantity of low materials needed in the economic dimension. All of them merged with social values, paradigm revolution, and relevant proposals of shifting the mainstream system of thinking based on values such as resilience, cooperation, and proximity.

Table 9. Multidimensional urban symbiosis concentric advantages

DIMENSION	ASSUMPTIONS	OBJECTIVES
Environmental	Urban Metabolism	Resilience
		Smallest ecological footprint
		Waste to energy conversion
		Lowest quantity of pollution
Social	Proximity	Resilience and social values
		Land efficiency
		Blooming employment conditions
Economic	Cooperation	Resilience and paradigms revolution
		Thriving flow material and energy mobility
		Decreasing quantity of raw materials needed

Cities that act in a short-term are trying to solve the problems they find in day to day planning and, in the best of the cases, over the four to six years that the democratic elected office allows. Like the industrial system, cities use to apply "end of pipe" solutions based on technology efficiency, they try to solve the problems with short-term and shortsighted solutions. However, supplying limited resources to an exponentially growing population is completely unsustainable over the long run. The production process, as we know it today, is a problem in itself so we need to think about *closing loops in water, energy, material, infrastructure and non-material resources (organization, communication, mobility, know-how, technology, etc.), sustainably in* order to reduce the amount of inputs that cities require to supply their production processes. We also need to think about dematerialization, decarbonization, and boosting the service economy in cities, reducing consumption among new urban structures. This is called urban symbiosis and is illustrated below in Figure 30.

Figure 30. Urban sub-ecosystems understanding at Sustainable cities



This potential urban symbiosis must not be associated to an ideal type or a perfect model; it is mostly one type of relationship in the ecosystem. Thus, to imagine a sustainable city we need to go beyond inputs and outputs flows (the study of metabolism) to reconnect sub-ecosystems. In fact, we do not have to create the conditions for a symbiotic relationship, as these conditions exist, as well as, the conditions for other types of relationships as (competitive, neutral, or cooperative). We only need to reconnect the links between the sub-systems. We have identified

11 different interconnected sub-ecosystems that operate in different types of ecological relationships: energy, climate, population, health, natural resources, education, transport, wastes, water, and habitat. It is possible to identify drivers, actors, and variables among the subsystems and to improve the synergies between the urban ecological subsystems. This approach studies the interactions between the different sub-ecosystems and the possibilities for fostering symbiotic relationships (symbiotic relationships are there; we just need to make them visible).

Boundaries

- There is no difference between public and private investment.
- The technology effect is incorporated as an external driver assumed of having regular increased effects in the system.
- The market and the consequences of the price changes on supply and demand consideration, this is assumed to be an external driver in the diagrams.

Comments

- Education is also considered as goods, services, energy, and transportation consumptions habits.
- Resources are considered as natural resources input.
- Security is understood as medical care access.
- Storage in the Transport/Storage subsystem also includes the parking lots and tourism accommodation.
- Population in the education subsystem could also be understood as family planning.
- Public area is defined as common spaces and infrastructure for citizens (parks, hospitals, libraries, streets, ports, airports, schools, service business, etc.)
- Private areas are designated as the places with restricted access in the city as houses, offices, industrial companies, etc.

Cities are currently spaces for the most consequential attempts at human adaptation and sustainability. The field of urban ecology is relevant; in 2014, 54% of the world's population was living in cities. Today, developed nations have about 74 percent urban, while 44 percent of residents of developing countries live in urban areas, and these numbers are rapidly growing, according to the United Nations, (United Nations, 2014). This is why cities are considered as perfect laboratories for an urban symbiosis experiments.

Some of the identified barriers to urban symbiosis might require developing improved technology or an issue of removing institutional barriers, and even of a long-term strategy in order to cope with some "locked in" infrastructures (Mulder, 2016).

Industrial symbiosis can be helpful to learn more about the emergence of interrelations. Over the last 15 years, the phenomenon of business co-location known as Industrial Symbiosis and discussed in the paper "Uncovering" Industrial Symbiosis of Chertow (2007), has generated much debate and raised some questions. The tendency is to steer public and private actors to choose projects with demonstrable kernels of self-organization that can emerge more fully as viable industrial ecosystems. Industrial symbiosis' studies corroborate that "eco-industrial" projects that involve significant material and energy exchanges, have rarely come to fruition in a sustainable way. Despite the potential to create highly structured industrial processes, the literature suggests not interfering in the natural evolution of companies or supporting through public or private investment projects that have much wishful thinking but no tangible kernels or preconditions[17] for an industrial symbiotic ecosystem.

This evidence source underlines the importance of market test to the potential recognition of industrial symbiosis in describing how different motivating forces, including the availability of specialized skills, the role of existing suppliers, scarcity conditions, and availability of natural resources, as well as chance, are involved in the success of an emerging symbiosis. However, it is important not to overestimate the relevance of economic variables up to the point of recommend zero intervention of public actors just because some evidence point out

[17] The preconditions and kernels of a cooperative symbiotic exchange network are usually the energy co-generation, waste, or water reuse.

that the self-organizing symbiosis model that builds from kernels of existing cooperation and exchange tends to be more successful than a formal planning model.

Considering this logic, if society should wait until free market drivers alone allow the self-organized industrial symbiosis to thrive as a strong sustainable development model, reflection about the following questions seems to be important: What if the emerged quantity of symbiosis is not enough? What if the industrial symbiosis never flourishes because the market drivers are mainly economic and underestimate the other dimensions, including social and environmental dimension? The following questions seem relevant for further research: What if those assumptions, as we have already known, are not relevant? Shall we just sit down and wait until the free market allows the urban symbiosis to begin on its own? Public actors and the community should focus on the conditions under which kernels and precursors have survived and thrived.

The public authorities and civic and private sector actors should play a lead role in the urban social system in order to identify and act on the balancing and reinforcing loops of the system, therefore, improving the general conditions of the social system and not just supporting specific companies or industries that seem to have synergetic potential. This is the factual link we uncover between cities and industrial symbiosis; moving forward to a multidimensional symbiotic relationship in the cities where energy, water, material, and people are submerged in a never-ending movement. Therefore, their interactions imply a mobility request in the form of transport and storage in boundaries, relationships, and behavior that can be depicted in a dynamic system.

CONCLUSION

In general, the methods and research output discussed here corroborates and expands earlier threads in the literature in finding that, in order to, get a better understanding about the symbiosis and the ecosystems where it could be developed, it is important to take a multidisciplinary approach in this complex field of study. The proposed entrance framework of study in this paper is grounded on industrial ecology, territorial ecology, and urban ecology. This combination of methodologies is prescribed to encourage the uncovering of urban symbiosis as an advantageous relationship, coexisting with other relationships in the city (competitive and neutral). This combination of methodologies is relevant for the emergence of sustainable cities, based on three different and successive approaches: (1) system dynamics (urban dynamics); (2) sustainable urban metabolism (mainly material and energy flow assessments), and (3) the Circles of sustainability model from James (2015), proposed to issue the interconnection between different subsystems in the urban ecosystem. These three methodologies enable the analysis and understanding of the urban ecosystem dynamic in a territorial perspective allowed by the socioeconomic and political system analysis of social structures, combined with the linear and physical analysis of social structures. The three methodologies are complementary because the strength(s) of one usually trades off for the weaknesses of the others. Nevertheless, to recognize the drivers and stakeholders of the balancing and reinforcing loops of those 13 identified subsystems in the urban ecosystem represents a complex problem, because the real social system cannot be depicted only using only quantitative data. Therefore, we certainly need to include qualitative data and the possibility measuring it in concretely through real-life city data. This is the advantage that the Circles of Sustainability methodology offers to a social system diagnosis employed with a system dynamic perspective.

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SECTION III – METHODOLOGICAL PROCESS

CHAPTER 4. WORK HYPOTHESIS

Who gets the benefits from an industrial and urban symbiosis? An embeddedness analysis in a sustainable city ecosystem

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ABSTRACT

The cities and their corresponding industrial systems are in the quest of sustainability, therefore industrial and urban symbiosis represent an alternative to reduce ecological footprint and pollution, improving land use efficiency and waste valorization drawing up a systemic approach. This paper seeks to establish a link between sustainable cities and Industrial symbiosis (IS) steering a new paradigm of sustainability through the analysis of its social embeddedness in the quest of social innovative strategies to sustain the emergence and endurance of industrial and urban symbiosis. The tools engaged in this study include the Social circles theory, the stakeholder's theory and the organizational theory that bridge the gap between the individual and the collective level of analysis, shedding some light over the dynamic systems for their better understanding (Forrester, 1969). The trade-offs dilemmas support the industrial symbiosis theoretical framework explaining the causality of its occurrence and emergence. The trade-offs hypothesis is validated through the By-product synergy case study in Altamira, Mexico, where we apply and gather a strategic set of interviews addressed to the stakeholders providing us with relevant insights regarding the circles of social life (James, 2015) and the strong (Diemer & Morales, 2014) sustainability theoretical framework.

Keywords: *sustainable cities, industrial symbiosis, stakeholder engagement, circles of sustainability*

INTRODUCTION

In Ecology, the symbiosis concept defines close and permanent interaction between two or more different biological species, like competition and parasitism. Those associations may - but does not necessarily - benefit the engaged member. i.e., symbiotic relationships emerge naturally in the ecosystem (communities of living organisms in association with physical environment, referred together in the paper as biophysical components). Since 1989, the industry understanding bears a resemblance to natural ecosystems, introduced by a paper published in Scientific American (Frosch & Gallopoulos, 1989). Even though the well documented relevance of energy, water, and material resources optimization, we aim to highlight the social dimension in this paper, standing out the natural ecosystem similarity with the social system. Technical applications, social sciences and the business management encompass the methodological pathway to encourage the analysis of sustainability in the industrial ecosystem (Diemer & Labrune, 2007).

Chertow has defined industrial symbiosis as "*engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by products*" (Chertow, 2007, p. 2). The theoretical framework' assumptions are based on the fact that industrial symbiosis follows a dialectic[18] logic, identifying the following axes: cooperation/competition, efficiency/resilience, local/global and top-down/bottom-up governance. Further researches integrate IS in the urban dynamic ecosystem to figure out how to assess the social dimension of cities with a systemic approach.

Insights out of this paper attempt to demonstrate that cities and territories influence and are strongly influenced by the industrial system, shedding light over the industrial and urban symbiosis studies (Berkel, Fujita, Hashimoto, & Geng, 1997). We define Sustainability in this paper as the human practices and meaningful commitments that generate a possibility of continuous natural and social flourishing, without threatening the basic conditions of social life in the long term (James, 2015). The understanding of the sustainability is a necessary step to encourage interdisciplinary cooperation between biophysical, social and applied sciences.

Indeed, a better social systemic understanding of industrial synergies is possible through the stakeholder's identification and motivations understanding figuring out the position of each

[18] Dialectical method looks for a transcendence of the opposites entailing a leap of the imagination of a higher level, which provides arguments for rejecting dualistic alternatives as false and/or helps elucidate a real but previously veiled integral relationship between apparent opposites regarded as distinct before wards.

piece in the complex industrial symbiosis fiber. With the stakeholders' divided for simplification purposes in four categories within the circle of engagement: (i) organizations and enterprises; (ii) civil society; (iii) governance institutions and (iv) research entities; standing out from the collected interviews that the industrial symbiosis process are the organizations and companies mainly represented by large multinationals, industry associations and public firms. Institutions and institutional adaptive changes (Ostrom & Basurto, 2011) help to clarify the controversial issues, encompassing the industrial system, through the internal and external systemic understanding of the social adaptive complex network of interactions.

LITERATURE REVIEW

Positive sustainability

We can find evidence of geographic and proximity embeddedness on sustainability social representation in the works of (Chalmeau, Julien, Vergnolle-Mainar, & Léna, 2016) and (Diemer & Marquat, 2016) addressing the voluntary and unintended commitment, setting up the social representations on the harmonization of idiosyncratic mental models. We recognize sustainability mental model as an interwoven set of information, opinions, attitudes and beliefs coming out from the social construction that looks forward to explain how the society explains reality (De Beer, 2018).

There is not a single representation of sustainability because there are several socially constructed realities belonging to different social groups, with specific strengths and weaknesses. Social sustainability is defined as "the society's ability to maintain" the necessary means of wealth to reproduce itself and, on the other hand, a shared sense of social purpose to foster social integration and cohesion (Ekins, 1997). Thus, we choose the best social sustainability representation (McMullan, 2008); picking the representation that entails the most consistent scenario in the realm of social expectations. Despite of the great available collection of representations, the social theory (Habermas, 1990) and the evolutionary process of knowledge (Vasilachis, 2003) agree that in despite of the huge diversity of social representations, a central paradigm usually prevails. Thus, the social representation of sustainability institutionalized by the dominant social group is in competition with the others peripheral representations.

To operationalize the paradigm of strong sustainability and not to fall in the same struggle of the previous paradigm, we adjust the model through different scales (global / local), objectives (cause / state / response) and degrees of complexity, avoiding conceptual ambiguities. The challenge we want to tackle in this study shed light over the internal cohesion and rational enlightenment in sustainability. One of the questions addressed in this article, is how to figure out a holistic approach for sustainability including the social and environmental issues. To answer this question, we propose the use of the circles of sustainability and circles of social engagement (James, 2015) as the theoretical framework to operationalize this transition.

Industrial Ecology

Industrial Ecology (IE) works as an analogy of biophysical ecosystems in industry, aiming sustainability (Frosch & Gallopoulos, 1989). IE stands out in four drivers: 1) waste's systemic valorization; 2) eco-efficiency increase (energy, pollution, by-products…); 3) functional economy (which means to shift from a product logic into a service one) and finally 4) low carbon energy strategy (Erkman, 2004) . Even when many experiences of IE have been spread all over the world since the 20th century, the amount of success stories is still very small, due to a misunderstanding of the process and motivational mechanisms into a specific context. Therefore we can assume that the more frequent hinders observed in IE whether technical, economic, informational, organizational, infrastructure or legislative nature (Duret, 2007) (Orée, 2013), are defined by the spatial and institutional context in which they are embedded.

The three-shared components of IE are: 1) the global integrated vision of the industrial system; 2) the total quantity and quality of flows and stocks of material, energy and information; and finally 3) the technology, as a crucial factor, facilitating the transition to a viable industrial system (Junqua & Brullot, 2015, 174). Some examples of qualitative and quantitative research methods looking to integrate the three previous components of IE has been documented in the following works (Schiller, Penn, & Basson, 2014).

In the literature review, natural ecosystems are presented as the only worldly example available to humans of long-lived, robust, resilient living system, representing the positive sustainability's related features. Our own human history offers no similar source for thinking. In the present study three collective trade-offs seem very important to regain equilibrium in the continuous adaptive ecosystems: cooperation/competition, efficiency/resilience and local/global proximity. Other characteristics are relevant in the dynamic process such as the governance in the social dimension.

IE analyzes social relationships, characterized by irreversible and dissipative flows in time and space, drawn-out beyond the immediate realm of necessity. The IE evolutionary perspective draw up its theoretical foundations within open dynamic systems (Forrester, 1969) organizational studies' theories (Freeman, 1994), the evolutionary perspective of ecological economics (Passet, 1991) and the management of change (Frosch & Gallopoulos, 1989).

Industrial symbiosis

Industrial symbiosis is a scientific field of IE that bridges the gap between applied and social sciences, interweaving the local sustainable development (Bahers, 2015, p. 244), and the biophysical exchange that promotes the flows and solid waste exchanges. To put this idea in practice, by-product synergy networks are today growing all around the world, either in defined regions or within industrial parks (Maillé & Frayret, 2015, p. 146).

In the paper we define Industrial symbiosis (IS) as a subfield of industrial ecology framed by the positive sustainability concept, going far beyond the Chertow's definition (2000) that highlight the technical and biophysical aspects engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or by products". Beyond the biophysical definition, we are convinced that the empowerment of the social process based on ecological, political, cultural and economic aspects is necessary for its better understanding of the industrial symbiosis process. Based on previous considerations we define Industrial symbiosis as the social innovative cooperative process spurred by the concerned stakeholders that aims to enforce the IE principles within a shared geographic, organizational and institutional proximity. Pushing forward the concerned firms to develop substitutive or mutual synergies, motivated by eco-efficiency and/or resilience, therefore high lightening the process feature driven by collaborative motivations and integrated in a specific territory.

ATTEMPTING SUSTAINABILITY IN THE INDUSTRIAL SYMBIOSIS

The concept of sustainability as understood in this paper is not fractal; we should stay aware of scales, because one territory could become sustainable at expense of another. Streamlining the positive sustainability understanding, we draw up the pillars for the microeconomic and social theoretic framework, which accepts the non-substitution between environmental, social and economic capital (Daly, 1991). Sustainability threshold changes according to the engaged scale, thus, sustainability in the microscale represents efficient allocation of ressources, marginal costs and benefits from an exchange value process, while in the macroscale seems to give answer to the quality of life challenges, i.e. territorial atractiveness, price level stability and governance. The systemic approach seems to bridge the gap, with a normative conceptualization that includes micro and macro dimensions.

Participatory and dynamic methods works on complex systems analysis for example, regional sustainability calls for territorial cohesion to preserve natural heritage without compromising economic development; while national sustainability calls for sustainable development under the analytical eye of systemic studies and technical parameters (Verger & Brullot, 2015, p. 324). Circles of social life helps us to identify the opportunities, threats, gaps, key decisions and hot questions that business as usual seems not able to explain, integrating the multidimensional perspective of complex scales (Soulier, Neffati, Bugeaud, Calvez, & Leitzman, 2015, p. 108).

The holistic and normative approach, which includes ecological, economic, cultural or political dimensions in Industrial Symbiosis seems able to inspire a sustainability transition in industry, starting from the local scale (Metereau & Figuière, 2015, p. 221). Thus, the socio-economic approach of IE should be framed on the assumption that industrial symbiosis' sustainability understanding is built over the following mean dialectic axes: cooperation/competition, efficiency/resilience, local/global proximity and top down/bottom up governance, emerging from an internally and externally coherent theoretical basement.

Local/global proximity tension: the territorial scale produces social representations according to the context. At the local level (microsocial), the governance mechanisms are applied to social actors (Joubert & Brullot, 2015, p. 39). The main barrier in communication within stakeholders' is the lack of coordination, according to Nicolas Buclet in the book (Ecologie Industrielle et Territoriale: stratégies locales pour un développement durable, 2011). The collaboration principle act between network's members letting the firms to go beyond their boundaries including external partners (suppliers, costumers, etc.). The IS implementation is a complex process influenced by several factors, like the nature of the activities, the history, the location, the coordination willingness and the organizational structure existence for industrial symbiosis stakeholders (Diemer, 2015).

Cooperation/Competition dialectic relationship: three patterns of IS relationship have been observed (Boutillier, Laperche, & Uzunidis, 2015): (1) ressource recovery network without common investment, (2) ressource recovery network with common investment, and (3) energy cascading network as a specific form of inter-company cooperation with common investment. Considered as a hybrid process in between competition and cooperation, we attempt to catch up the balance between social and economic sphere since this symbiotic networks are shared by public and private interests, in order to find a different sustainable paradigm where the IS exeptions could became the norm of social cooperation/competition.

The social structure is not a linear model, applying the metaphor of circular cooperation / competition used in IS generating products, by-products, emissions, wastes, profits, wages and taxes, but at the same time consuming raw materials, inputs, energy, capital, labor force, social organization and revenue from the product sales. Customers pay for products and services, which represent the revenue of the organization. Society, represented by the state, collects all types of taxes (Madison, 1906), and responds with a normative social organization, because it has a legitimate monopoly on the use of force and authority. Workers provide their work (intellectual and physical) and receive wages, salaries and benefits, when the owners receive profits and interest reinforcing the value the commodification behavior.

Governance jeopardy: top down/bottom up: two main assumptions hinder sustainability (Lambert & Boons, 2002): 1) sustainability improvement is easy in the short term (side social changes); but in the long term it frequently go back to their ancient behaviors, because of their institutional attachment to a business as usual streamlining. Thus, to trigger a system's change instead of its optimization, we should get away from the current system, what necessarily depends on the involvement of all actors in the changing process. The governance in the IS soes not simply regards the stakeholders' conflict of interest, generally think on their individual interest. Moreover, the success of the IS is mostly related to the sustainability governance strategies, driven by their responsibilities and commitment on moral and ethical issues. This success is also based on the enabling context (Boons & Baas, 2006) which can be described in terms of ecological, cultural, political and economic embeddedness of actors, involved in government (and other institutions).

Dialectic harmonization between resilience and efficiency: resilience[19] in the ecological literature determines the persistency of structural relationships in a system; therefore it becomes a measure of the ability of these systems to absorb changes". Resilience emerges during the transition of an ecosystem between two adaptive states. When the first equilibrium state is lost due to a perturbation, the system must react to regain an equilibrium state (Holling, 1996). On the other hand, productivity is based on the concept of global efficiency, merging economic, cultural, political and biophysical criteria (Diemer & Morales, 2016) but also grasping the social productivity understanding. The systemic resilience depends on structural issues, encompassing diversity and redundancy; therefore, to guarantee high resilience, it is vital to assure redundancy for key functions. In this study, we describe the Altamira By-product Synergy as a complex ecosystem able to evolve over time, with firms playing the role of organism and performing specific functions. These functions entail: 1) to create economic benefits for firms (organisms); and 2) to create environmental benefits for the collectivity (external environment). In this study the analysis of resilience only makes sense when applied to a social system, thus, resilience would be the structure that emphasizes industrial ecosystem's responsibilities concerning the involved stakeholders at the community and the economic stakeholders' responsibilities'' (Turban & Greening, 1996).

ALTAMIRA-TAMPICO, PETROCHEMICAL OVERVIEW

Altamira-Tampico industrial area in the state of Tamaulipas is one of the most important trading ports in Mexico with more than 30 transnational companies. The most relevant institutions in the local development are the Madero Refinery, Altamira Industrial Park, the Altamira Industrial Port and the AISTAC.

[19] Defined as the capability of a system to absorb disruption and reorganize while undergoing change to keep essentially the same structure, function, drivers and flows"(Holling, 1973).

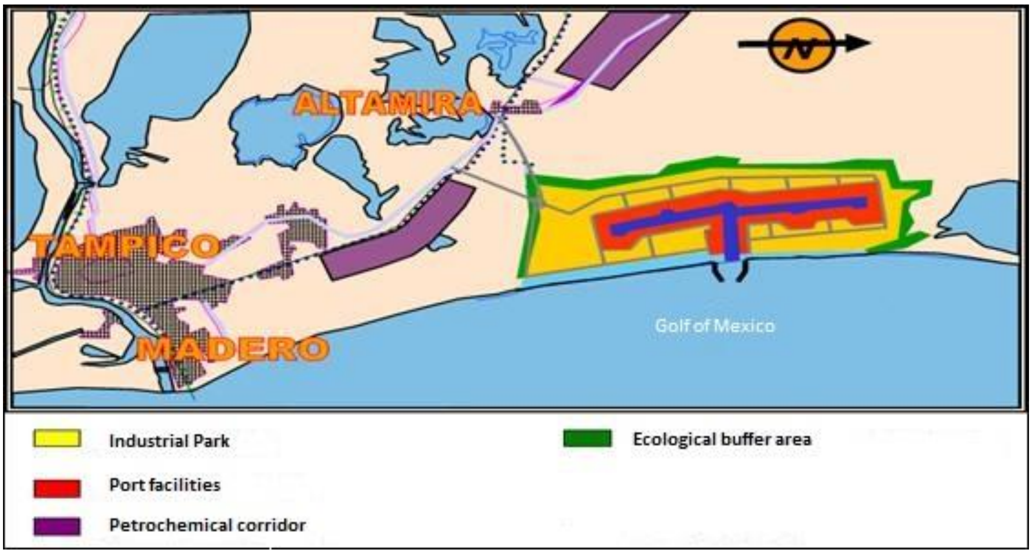

Figure 31. Location of the Altamira Petrochemical corridor.

Source: Altamira Industrial Port (2005)

The Madero Refinery is one of the industrial vital organs, with an annual capacity of 7.5 million tons of crude oil and refined products. Indeed, the refinery was restructured between 1999 & 2002 to reduce air and liquid emissions and surface water consumption, thus helping in the supply of regional unleaded gasoline. To meet the Mexican environmental regulations, electric facilities and infrastructure shift from high sulfur fuel oil to natural gas, therefore increasing fuel production at the expenses of oil production decrease, attempting the enlargement of the refining capacity.

The Altamira Industrial Park encompass a set of large-scale production companies, holding around 20 large private companies (BASF Mexicana, Biofilm, Flex America, Absormex, Dypack, la Esperanza, Fletes Marroquin, MASISA, Iberdrola, Kaltex Fibers, Mexichem, Polioles, Posco Mexico and Sabic Innovative Plastics Mexico). Altamira Industrial Port was built in the 80´s, taking advantage of its strategic location, 500 km. away from the US border, guaranteeing access to North American market. The Altamira Port entails a navigation area of 30% and moves more than 6 million tons., every year.

Altamira Petrochemical Corridor counts 10 multinational corporations that represent nearly 25% of private petrochemical production in Mexico and almost 60% of all exports in basic petrochemical manufacturing (CRYOINFRA, INDELPRO, M&G Polimeros Mexico, Chemtura, McMillan, DUPONT, DYNASOL, CABOT, Enertek and Petrotemex) in Altamira

BPS. The emergence of the petrochemical corridor took place in the 70´s with the establishment of the firms Dupon, PETROCEL and Hules Mexicanos. The industrial association known as AISTAC was founded in the 80´s, gathering some of the largest companies in the South of Tamaulipas state, facilitating firms' interaction and acting as anchor tenant between industry, community and local authorities.

METHODOLOGY

The Engagement circles, is a methodology part of the circles of social life method, developed by Paul James in the (Urban Sustainability in Theory and Practice: Circles of Sustainability, 2015) encouraging the study of sustainability transition endorsed by the meso-level structure. The integration of macro-level feedbacks (Schiller, Penn, & Basson, 2014) in the social sciences, comes out from the assumption of context dependency and domain-specificity, therefore most of social studies based on case studies brings about specific challenges like the generalization from small samples.

To overcome the difficulties regarding the generalization of conclusions coming from small samples, case studies needs to be approached in an objective way based on social theory, standing out the commitment and coordination of stakeholders in an innovative way. It is necessary to be aware of some risks like the ethnocentrism and the oversimplification of the analysis potentially resulting from this methodology. Moreover, the circle of social life method is a powerful tool adapted to large territorial boundaries and it usually offers satisfactory answers to complex questions. (Joubert & Brullot, 2015, p. 42)

The circles of social life method is identified in the literature as one of the most promising methods to accomplish industrial ecology integration across disciplines with a coherent narrative string. The systemic approach of Circles of social life result interesting when territorialy defining sustainability and figuring out the stakeholders' influence in the urban ecosystem. The tools mutualisation offers a coherent understanding of IS complexity in situ (Verger & Brullot, 2015, p. 323), enhacing the viability, coherence, clarity and efficiency at the local sustainability assessment process (Gombert-Courvoisier, Sennes, & Ribeyre, 2015).

RESULTS

This study is organized in the form of direct interviews to stakeholders in Altamira By-products synergy (Annex 1), identifying the stakeholders involved in the social structure, depicting a process that is not simply economic. With this aim the data was collected in 2016, identifying four different social dimensions: ecological, economic, political and cultural (James, 2015). The novelty of the territorial studies, like circles of sustainability, is the adoption of a systemic logic that breaks with the mainstream causal analytic thinking by considering their contingent relations. The episthemological opposition brings on board the needs towards a dynamic science (Joubert & Brullot, 2015, p. 42), attemptiong to improve the local industrial ecosystems understanding.

This chapter provides an analysis of stakeholder engagement in the Altamira Petrochemical Corridor, regarding the evolution of a petrochemical industry that deals with non-renewable fossil resources. The IS encompasses 10 transnational petrochemical industries, the AISTAC, the research, education and governance structures and the local community. Half of the transnational petrochemical companies of the ISN (CABOT group, M & G Chemicals, INDELPRO, INSA), the AISTAC, a university and the research institute CICATA as well as the local government represented through the local Ministry of Economic Affairs and Employment have contributed to this process.

With a good knowledge of the community and the industrial symbiosis process, more than 30 years living there and 17 years of experience working in the host firms in average; the participant's interviews were recorded, analyzed and interpreted using for this project the text analysis software called Tropes for qualitative text analysis. According with the question and objectives attempted, different graphs and diagrams were proposed to draw up the stakeholder's circles of engagement displayed below (Figure 32).

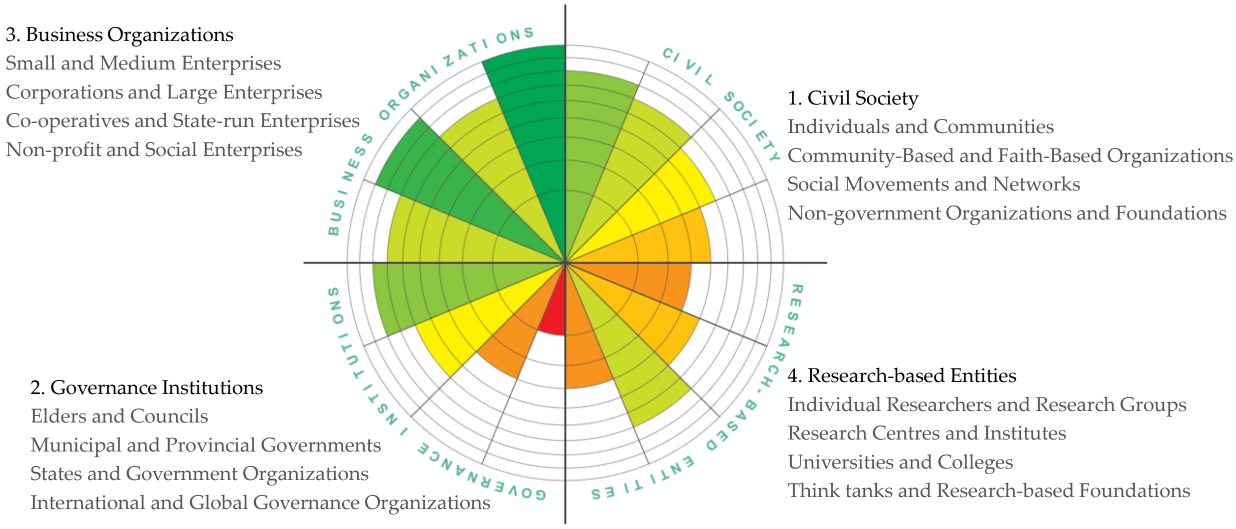

Figure 32. Social Stakeholders' engagement circle

Stakeholder's engagement analysis in the Industrial Symbiosis

In this study, the IS's stakeholders entail four categories: Governance Institutions, Civil society, Business Organizations and Research-based Entities. Governance Institutions, represents an important part of the society that collects all types of taxes in response to the legitimate monopoly of force and authority. Civil society, determines the social structure by defining the quantity and quality of jobs (direct and indirect), customers, markets including preferences' identification. Research-based entities include universities and research centers defining not only the industrial systems but also the urban system in which industry is embedded, through education and culture.

Ecological dimension

Insights in this dimension entail stakeholders' ecological commitment to IS, looking for generalizations. The first issue regards the stakeholder's engagement with the raw materials origin, supplies and inputs used in the production process of the IS in Altamira. The lines in Figure 33 shows the relationship between the object and the author. A dotted line shows a low frequency relation and a solid line indicates a frequent relation, without disregarding that only the most significant references are shown in the graph.

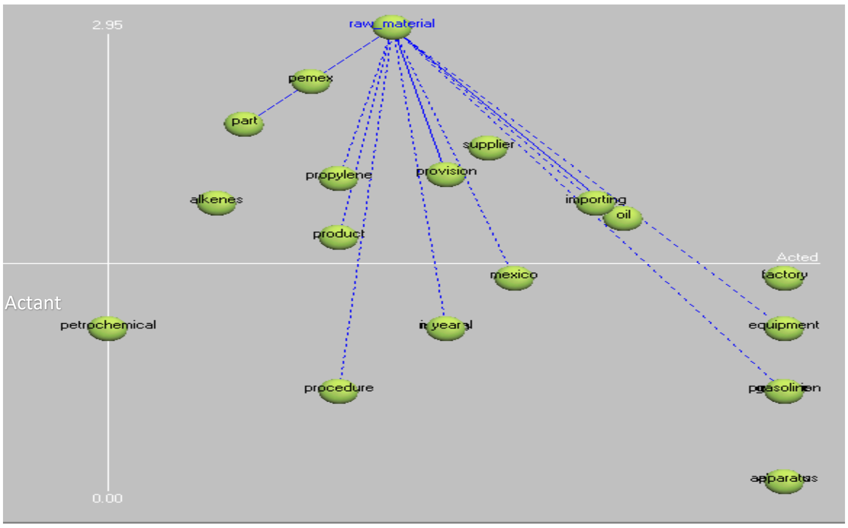

Figure 33. Actor graph on raw material origin in Altamira Industrial symbiosis

From the graph, we can assume that most of inputs in Altamira Petrochemical Corridor comes from PEMEX, posing serious quality and availability problems. Other insights depicted from the graph lead to the minimal use of clean or renewable energies in the region; a lack of stewardship in the energy transition strategies is remarkable in the industrial symbiosis, limiting the collective efforts to energy cogeneration projects encouraged by the CFE.

Indeed, the stakeholders' present a strong engagement for the quality of water and air standing out an optimal performance strictly respected by the industry, assured by a strong legal normative. The water issues are quite more complex in the region, because its quality, price and availability are influenced by the geographical location. Currently a struggle about the price of water takes place within the industrial community, regarding water quotas increase in the region (more than 300% in a one-year period due to a reformulation of the variables and criteria for water tariffs calculations). With important effects on the petrochemical productivity, because of their high water consumption.

The most popular investment strategies implemented in the region to improve and protect the air & water quality are the "end of pipe" strategies, for example: water treatment plants, high technology filters in industrial smokestacks. All these investments seek to obtain an economic turnover in the short term, even if there are exceptions like industrial synergies, which have trade-offs with environmental aims like the water synergies between CABOT, INSA, INDELPRO and PETROTEMEX to encourage the water extraction reduction directly at the source.

Figure 34. Area Graph on air and water improvement strategies in Altamira Industrial Symbiosis

Regarding the engagement of stakeholders in transport and people’s mobility, the community calls up for better legislation and control of private transport, bringing up some interesting points of view about the public transport management by private companies that underestimates people's access to mobility. Overall, civil society complains about the public authority lack of control and concerning public transport services, thus firms engage in cooperative mechanism to pursuit alternative solutions to local mobility problem. In this sense, firms provide the means to develop a free collective transportation service for employees.

Economic dimension

Figure 35 displays the economic engagement of stakeholders at the petrochemical industrial corridor, standing out that a relevant share of economic benefits comes from the valorization strategies, and not just from the technology trade-offs in the industrial network. Spill over benefits such as lateral knowledge (Mauelshagen et al., 2014), expert advice, pooling services projects through economies of scale, boost the industrial symbiosis, shedding light over the strengths of a shared common language and the improvement of the communication skills.

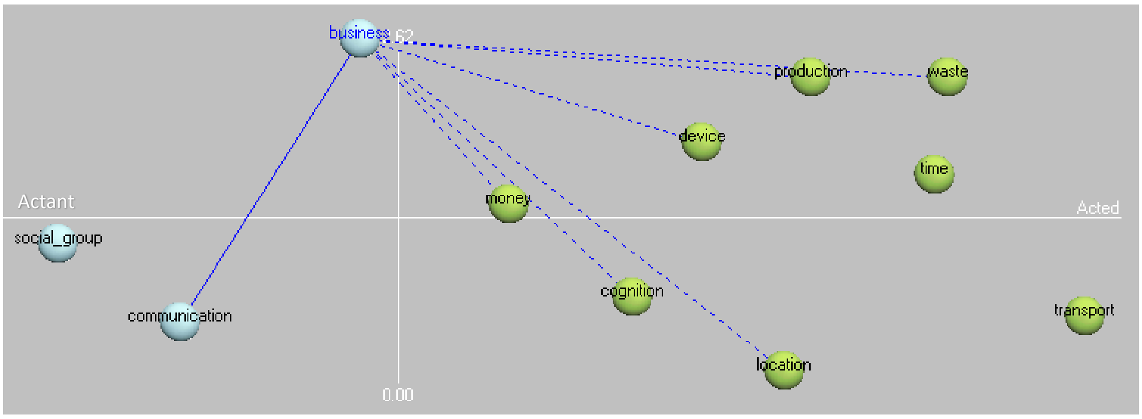

Figure 35. Actor graph on economic benefits of the Altamira Industrial Symbiosis

Costs reduction in one of the attended effects in the production process of IS members thanks to the emergence and endurance of sustainability in the Altamira IS, even when the monetary savings are reduced; stakeholders usually obtain some positive spillovers related to business social responsibility and socio-environmental care. An interesting insight provided by the stakeholders is the role of formal contracts in the endurance and confidence between stakeholders, supported by a strategic communication, which is coordinated by the AISTAC. Even when good intentions of firms are not questioned, unexpected situations could emerge in the interfirms' relationship and it is better to be clear and prepared about the way in which actors could respond in order to minimize uncertainty and risk. Thus, underestimations could be translated in economic struggles and misunderstandings, easily avoidable if discussed beforehand.

Technology plays a relevant role on the production process improvement; i.e.: the water use and disposal, as well as the development of communication skills necessary to accomplish the exchanges in the IS. In addition, the discussion arena facilitated in the monthly meetings organized by the Technical Committees of AISTA, make possible the experience and knowledge share. Private companies federated in the IS do not feel the engagement and support from the public subventions and aids, because there are only a couple of firms that have taken advantage of federal programs.

Political engagement

The role of stakeholder in the IS is fundamental; considering that a lack of facilitator and couching could steer the symbiosis towards an ancillary role. Furthermore the academia and research institute in cooperation with the practitioners, develop business protocols and guidelines, providing normative feedback to petrochemical and waste management legislation. The political actors encourage a common language to enhance the understanding of social issues, standing out education at the center of sustainability. Strategic plans and emergency response protocols provide certainty to private and public stakeholders in the symbiotic process, for example: protocols in case of natural disasters, fire, or explosion

In this study, we consider the granularity of the processes, not as additive steps, but as a systemic interrelationship leading to the build-up of participatory scenarios. There is a strong interrelationship between the leader's behaviors and the political context, because leader's values usually helps to clarify the shared values in the company.

Cultural engagement

Research and development investments are not enough in Altamira BPS, because multinational companies usually invest this budget in the headquarters' offices, transferring afterwards the outcomes to the industrial plant. The technical applications usually arrive without an adaptive technology and lacks of regional values integration; another common strategy is to outsource the research for a specific technological improvement in the process, through a *"key on hand contract"*, usually with foreign technology. There is a clear link between stakeholders' ideological foundations and the environmental responsibility related to Industrial symbiosis; however, the existence of a gap between "modern" values spread in the business sphere and the agrarian traditional values, threatened instead of integrated. The mentioned modern values concern efficiency, productivity, security, progress, modernity and fast-speed change, in opposition with the agrarian values still prevailing within some social stratus identified as calm, quietness, resilience, nature balance, traditions, respect, slowness and social active participation. In the context of Altamira industrial symbiosis, the industry has proved to accept the influence of those local values.

CONCLUSIONS

The Stakeholder Engagement Circle is a normative social analysis methodology where the integration of structure and roles takes place in a dynamic urban ecosystem. In order to preserve the objectivity and comparability of data, and to move away from the subjectivity in the analysis as "structural determinism" we propose to integrate spatial proximity to our ecological, economic, political and cultural reflections.

Recent IS approaches, recognize the importance of setting up a solid and coherent theoretical framework for sustainability, identifying the industrial symbiosis as one of the key drivers for bridging the gap between abstract theoretical framework and systemic sustainability implementation. Without disregarding that in a growing industrial system, success from symbiosis will not last if the total metabolism is still growing or even worse, if industrial symbiosis directly increase total throughput (Shi, Chertow, & Song , 2010). The risk of rebound effects boost because industrial symbiosis represents a form of energy/material exchange and trade off with underpinning efficiency gains and cost reduction backfire effects.

The engagement, function and structure in the industrial symbiosis has carried out many structurally complex studies at the micro- level but few equivalent studies at the macro-level. According to the related social framework, the behavior patterns of stakeholders end up steering institutional changes in the continuum between markets and government, determined by the social structure.

One of the mean observed features in the social approach of the Altamira's industrial symbiosis stands on the fossil fuels scarcity underestimation, considering that it is the current main input for the petrochemical process. After a social analysis of stakeholder engagement, evidence shows that pathway dependency influence the process of industrial symbiosis occurrence, and are explained endogenously by conditions such as stakeholder motivation, network structure, size, type of governance, trust, among others. Bringing about, a pre-analytical vision of interactive industrial systems, which seek for the adaptive balance between: (1) participatory and central governance strategies, (2) productivity and resilience, (3) local and global and (4) cooperation and coordination as exchange strategies.

We can conclude from the data obtained in the Altamira IS interviews that the social sphere of sustainability could only be evaluated in a dynamic way, and for this purpose is important to choose one of the methodologies able to integrate complexity. In the toolbox of complex adaptive social systems analysis, we can find the Social Circles of sustainability (Figure 32). The present study stands out the stakeholders' interrelationship in a dynamic and systemic environment, especially at a micro scale and with clear social and biophysical boundaries.

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CHAPTER 5. ALTAMIRA BY-PRODUCT CASE STUDY PATH DEPENDENCY ANALYSIS

"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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Full Length Article

"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.

ABSTRACT

The ABP Industrial Symbiosis is a good example of industrial collaborative network system. Its historical outline presents four different stages: Emergence, Regional efficiency, Regional learning and Sustainable Industrial District with different mechanisms and motivations driving each of those stages in a broader systemic industrial symbiosis outlook. The industrial project at Altamira-Tampico may be considered as a socio-technical and environmental model, which embodies one of the most complete biophysical, social and economic symbiotic case studies in Latin America. In a centralized and ancillary industrial symbiosis kernel process like

the Altamira one, the marginal efficiency tipping point appears at the Regional efficiency stage, with the highest employment and by-product exchange rate. Therefore, an eco-innovative ecosystem strategy, encompassing small and medium size firms is suitable for territorial attractiveness, where the successful mechanisms for improving learning and innovation, decreasing transaction costs, and increasing flexibility boost.

Keywords: historical analysis, industrial symbiosis, eco-innovative ecosystem, learning process, transition phases.

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; Beaurain, Brullot, 2011; Boons et al, 2016; Diemer et al, 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, which can replace raw materials in an industrial system, to reach a natural closed ecosystem (van Berkel, 2010). More recently, Diemer and Morales (2016) 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, Morales, 2017).

If industrial symbiosis has often been associated with industrial metabolism studies (material and energy flows, input/output models, life cycle analysis) or efficiency improvements, much attention is focused today on the social context and the dynamics of the learning process. The connection between biophysical exchanges and social interactions has been successively analyzed by Sterr and Ott (2004), Gibbs and Deuz (2005), Hewes and Lyons (2008), Shi et al., (2009), Boons and Howard-Grenville (2009).These authors prefer to highlight the social dynamics within a symbiosis rather than the economic benefits or technological 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 ISRS in San Francisco, which was organized by the ISIE section of the Yale School of Forestry and Environmental Studies. The emergence of the innovative learning process introduced a new focus on industrial symbiosis studies, 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 the paper is to explore the social context and the learning process of Industrial Symbiosis (IS) to offer insights into the complex interactions between actors and organizations. 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 make us forget that there are key social drivers that facilitate this pathway. We refer to an empirical case study, the 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 flexibility.

This paper starts with a diagnosis of the Altamira By-product industrial symbiosis, identifying the characteristics, stakeholders, motivations, mechanisms and the amount of symbiotic exchanges (mutualistic and substitution) taking place at that moment. However, a static picture of the industrial ecosystem is not enough and an historical analysis support the study in order to better appreciate the industrial symbiosis transition in Altamira over the time, considering the current state as an historical sequence of consequences in the industrial ecosystem process. This historical analysis use as proxy the employment rate for the entire network and the amount of material and energy exchange flows, as a way to approach industrial development and attractiveness in the territory. Once the interpretation proposed, we enlighten some innovative strategies and mechanisms to boost attractiveness and sustainability in the Altamira industrial ecosystem in the sought for self-learning, eco-innovation, decreasing transaction costs and increasing flexibility. We are convinced that historical analysis is highly recommended, especially for social processes, and it provides better understanding of the system feedbacks and driver mechanisms involved in the industrial ecosystem.

Three questions served 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 of the process affect the functioning, organization, and perspective 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 dynamic at Altamira.

LITERATURE REVIEW ON INDUSTRIAL SYMBIOSIS DYNAMICS

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 called 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 must 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 consist of a continuous stream of co-operative efforts through which a group of actors advanced their understanding of how to assess social, economic and ecological aspects of their decisions in an integrated way. If, ideally, each of the co-operative efforts contributed to the progress of the group of actors towards sustainability, Lambert and Boons noted that in practice, 2 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 able to balance 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 2 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), 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, regional industrial system) and focuses on changes that influence the system. About 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 3 following stages. The first stage, *regional efficiency*, is described as autonomous decision-making by firms which includes coordination with local firms to decrease inefficiencies (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[20].

This analytical framework helps to analyze regional industrial system (Boons, 2008) cases and to explain the different alternatives to 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 4 sets of forces which drive the success of a region: (1) *company strategy, structure and rivalry* - which determine how companies operate and interact with each other; (2) local market demands - which influence the quality of goods and services produced; (3) *the availability of factors of production* - natural resources, labor, capital, and infrastructure to meet supply needs; (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 what are the acceptable standards and practices. Complex system theory is useful to look at interactions between actors at multiple levels and to examine how those interactions shape and change system structure and functions (Holling, 1987, 2001). Thus, Ashton considers that a regional industrial ecosystem may be conceptualized as a complex adaptive system with diverse self-organized subsystems (including firms 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

[20] 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.

against perturbations and disturbances. This framework is interesting but we have identified 2 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 4 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 into 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; Coelho et al., 2017).

(2) If 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, 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 put up 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. 2011). 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 R., Poyyamoli G., 2015) They 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 resources (availability and sharing of knowledge), (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: (1) constraint - an organization is forced to adopt routine rules of another organization that holds power within the symbiosis process; (2) imitation - an organization adopt routines and operating procedures as a result of observing the practices of other organizations; (3) governance of private interests - organizations may choose to collectively adopt a rule or routine due to the threat of legislation; (4) public initiatives - political actors can initiate experiences and practices and then disseminate the results in the form of "good practices" to accelerate public acceptance; (5) training and professionalization - people learn new concepts and techniques; (6) altering the boundaries - actions stimulate the actors of regional industrial systems in a self-organizing way.

These mechanisms seem to play a key role in the conception and the diffusion of industrial symbiosis, they open a very large research field 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 that "Industrial symbiosis engages diverse organizations in a network to foster eco-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 that area 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 actors are represented by nodes and ties depicts connections between them (Ashton, 2008).

Secondly, these mechanisms detailed in Table 10 may help us to build a description of the dynamics of industrial symbiosis, showing the initial actors, the actors' motivation, the overall history, and typical outcomes (Boons, et al., 2016) listing 7 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 Eco-cluster development.

Table 10. Seven types of industrial symbiosis dynamics

Dynamics / Typology	Initial actor(s)	Motivation of the initial actor(s)	Following actions/overall storyline
Self-organization	Industrial actor	See 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]
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 interorganizational 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.
Facilitation 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 nonlocal 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 colocated 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 to other groups of collocated industrial actors.
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 eco-cluster→ symbiotic linkages are developed through participatory process among multiple stakeholders as part of the broader eco-innovative strategies.

Source: Boons et al., (2016)

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 Eco-cluster 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). A participatory process seems essential to resolve any problems or conflicts between actors and to engage them in a cluster of companies.

Taddeo et al., (2017) compared the dynamics of industrial symbiosis and the main characteristics of (regional) industrial clusters. Three study cases (chemical, automotive, and agri-food industries) located in the Italian Region of Abruzzo were described. 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) current context (structural factors like the nature and the characteristics of the processes, and the material and energy flows); (ii) previous context (factors and forces that are embedded in people and organizations: culture, experience, knowledge, roles, rules, routines); (iii) future potential context (perception of the local stakeholders of future effects/potential benefits). From the three previous cases studied by Taddeo et al., (2017), the key drivers are: geographical and technical requirements (strategic location, resource availability and the presence of utilities in the industrial site); homogeneity/heterogeneity of industries (number of industries and processes involved in the industrial symbiosis); active participation of stakeholders (local governments, agencies, key actors, local communities); regulatory system (environmental legislation and standards). In summary, the structural factors that play the most relevant role in the development of industrial symbiosis are: (1) proximity of production plants; (2) infrastructure, utility and service's availability; (3) the wastes' volume and homogeneity; (4) the limited presence of hazardous materials and; (5) the willingness of companies and stakeholders (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 Grenville (2009), Boons et al., (2011), Boons et al., (2016), Taddeo et al., (2017). We identify stages of construction, types of actors, and underpinning motivations in the industrial symbiosis, supporting our results through the evidence found in the Altamira case study. 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. However, we include another stage before Regional efficiency, which we term Emergence. We have 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 Grenville, 2009) may be useful to address some key questions: 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 strategies should be recommended to businesses or public actors to facilitate the transfer and learning process? We introduce 2 levels of social process in the development of industrial symbiosis – RIS and SL – proposed by Boons et al., (2011), even if the analysis of routines and standards is not complete. We suggest 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 analysis of its evolution.

CASE STUDY CONTEXT AND HISTORY

Kalundborg (Denmark), which started in the 1960's, is often described as the success story of industrial symbiosis (Branson, 2016, Jacobsen, 2006). Other industrial symbiosis projects emerged in the 1990's like the BPS project in Altamira (Mexico), started in 1997 by the WBCSD-Gulf of Mexico[21]. 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.

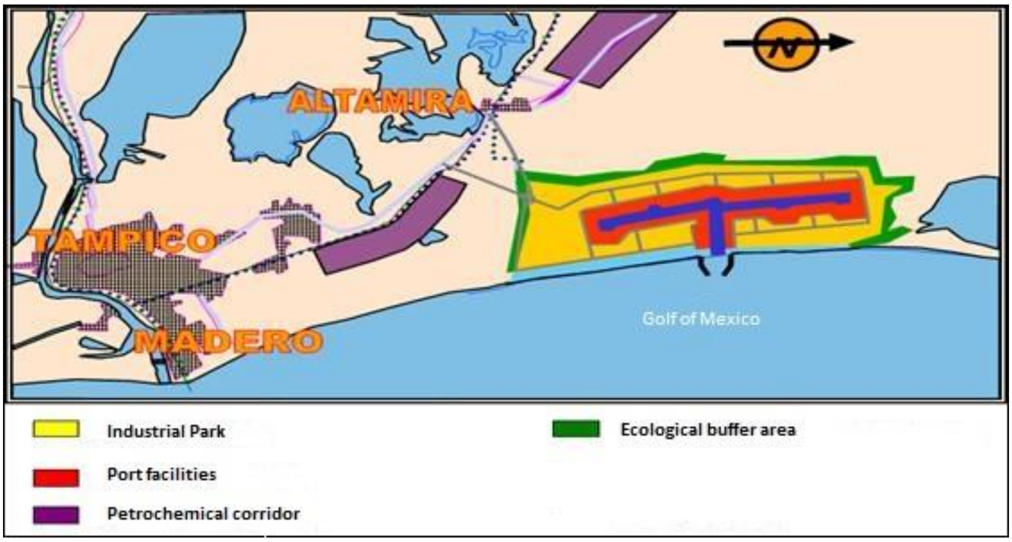
Altamira-Tampico, Industrial Corridor Framework

Because of its strategic location, the Altamira-Tampico area in the state of Tamaulipas is one of the most important coastal industrial zones in 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 Figure 36, are the Madero Refinery, Altamira Industrial Park, the Altamira Industrial Port, the Petrochemical corridor, and the 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, Baker, 1999).

[21] From Mangan and Olivetti (2010), the WBCSD-Gulf of Mexico 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.

Promoted by the WBCSD-Gulf of Mexico the Altamira BPS project aimed, in its early stages, to identify a minimum of 5 synergies, foster greater understanding of eco-efficiency, and create a new community of companies with better industrial leadership.

Figure 36. Location of the Altamira Industrial Port Cluster



Source: Altamira Industrial Port (2005)

The Madero Refinery is one of the area's vital organs, 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 refinery was upgraded and modernized between 1999 and 2002 to substantially reduce air and liquid emissions, and 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 project was supported by EX-IM bank in the United States.

The Altamira Industrial Park is the strategic integration hub in the region. The cost/benefit rationale overwhelmingly favors large scale production companies and long-term investment. Approximately 500 hectares were provided with basic services, such as water, electricity, gas and roadways, and made available. The Altamira Industrial Park has approximately 20 large private companies (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, is one of Mexico's preferred trading ports, built in 1980 its strategic location, only 500 km from the US border, as well as being close to the main economic centers in Mexico, allows for speedy access to any markets in the world. The port uses only 30% of its total area of 3,000 ha and more than 6 million tons of cargo transit through it every year.

Altamira Petrochemical Corridor has 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 starting point of the petrochemical corridor was in the 1970´s with the establishment of Dupont, PETROCEL, and Hules Mexicanos, stimulated by the construction of the Altamira trading port.

The AISTAC is an organization funded since the beginning of the 1980´s, it represents some of the largest companies of the South of Tamaulipas state area and acts as a link between industry, community, and local authorities. The AISTAC is strongly linked to the Altamira Petrochemical Corridor development.

As pointed out by Frosch and Gallopoulous (1992), 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 corridor operates as an open system subject to the entrance of energy: the petrochemical industry processes a flow of non-renewable fossil fuels, and they have started to search for a recovery and recycling strategy. The economic, social, and environmental benefits, according to some analyses, are still limited.

HISTORICAL OUTLINE AT BPS ALTAMIRA - PHASES AND TYPOLOGIES

The historical understanding of industrial symbiosis is based on combined biophysical, social, and economic dimensions which are associated with 4 different phases and typologies of industrial symbiosis, as shown in Table 11.

For BPS Altamira, phase 1, the "Emergence phase" (1997-2006), was linked to the starting point of the 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 was perceived as a high potential opportunity, mainly because of the geographical proximity. Other positive factors, like the existence of the AISTAC with its more than 20 years of experience, the common environmental concerns shared by the companies, the companies' collective interest in identifying cleaner and more efficient processes, and the leadership of Mr. Prieto, a business owner pushed the companies into the creation of high quality "commodity" and cost reduction processes, and into looking for collaborative efficiency improvements. In phase 1, the BPS identified a total of 373 material flows, the atmosphere of trust was strengthened, and enthusiasm was generated to cooperate in the project. Of the output flows 120 were wastes from 78 different materials, and 54 were end-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-Gulf of Mexico did not go into the detail of the social dimension, even though the key actors' roles were underlined in the emergence of industrial symbiosis.

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 AGSEO at the Metropolitan Autonomous University and the GIEI at the National Polytechnic Institute. The supporting role of the research educational institute 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, in which 29 material flows were identified, 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, 1999). Other sources of change were the regulation pressures implemented by public agencies, and other institutions which developed Mexico's environmental policy, and the adoption of stricter environmental strategies. Some of the research questions formulated during this period time were: Which factors assure the good performance 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 dynamic?

Phase 3 was the Regional learning (2011-2015), where the evidence suggested a turning point in the industrial symbiosis typology "Facilitator 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 fall back into their old patterns of behavior over the long term due to their embeddedness in an institutional context. Second, firms found that to ensure the system's structural change rather than system optimization, changes need to emerge from the current system. Thus, every actor 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 state of learning, facilitated by AISTAC communication, and the coaching skills developed.

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 search was for improved resilience in the process through the diversity of activities and actors involved in the BPS network. A change toward sustainability is difficult to achieve in the Altamira petrochemical BPS due to the actors' divergence of interests, competing technologies, and by-products, which make companies' synergies particularly difficult. The fact that Altamira's synergies are restricted mainly to ancillary processes, is one of the evidence of the difficulty of industrial symbiosis, as supported by the Rotterdam IS analysis of Baas et al (2004).

Phase 4, 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 outlook called Sustainability of Industrial District (2016). This decision 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 Eco-cluster 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 global and interconnected dimension that industrial symbiosis brings to the social dimensions of industry's 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 Eco-cluster with a broader range of firms, including small and medium sized firms as potential stakeholders of the Eco-innovative strategies.

Table 11. Four phases of change at BPS Altamira, characterized by typology, motivations, initial actors and overall history

Dynamic	IS type	Motivations	Initial actors	Overall history and outcome
Emergence (1997-2006)	Facilitator / brokerage	Inter-firm organization and transparency	WBCSD – Gulf of Mexico	- The early stages of the possibility of industrial symbiosis development - 21 companies engaged in the project identifying 373 potential material flows: 199 inputs and 174 outputs, the atmosphere of trust was strengthened and enthusiasm was generated to cooperate in the project.
Regional efficiency (2007-2010)	Facilitator /collective learning	Eco-efficiency and environmentally friendly practices	The BPS has 21 firms at Altamira project and the AISTAC	-63 more potential synergies identified by the research groups and stakeholders. -Inclusion of the research community -Increasing environmental pressures and regulations from government. -By-product reutilization and decreasing wastes expected.
Regional learning (2011-2015)	Facilitator / collective learning	Resilience	The 6 most engaged firms in the BPS Altamira project and the AISTAC	-Decreasing number of biophysical exchanges and in the value of these transactions. Only 2 new byproduct exchange projects (developed by INDELPRO and CABOT). - Industrial symbiosis limited to ancillary products and not related to core activities and processes.
Early phase of definition of the Sustainability of industrial district (2016 up to now)	Eco-Cluster development	Adaptability and flexibility	BPS Altamira current members, AISTAC, external participants and local authorities	-Decreasing marginal efficiency of environmental investments. -Altamira municipal government contribution necessary to develop a strategy for the development of an Eco-cluster with a broader range of firms, including small and medium sized firms as potential stakeholders of the Eco-innovative strategies.

A dynamic methodology for industrial symbiosis analysis

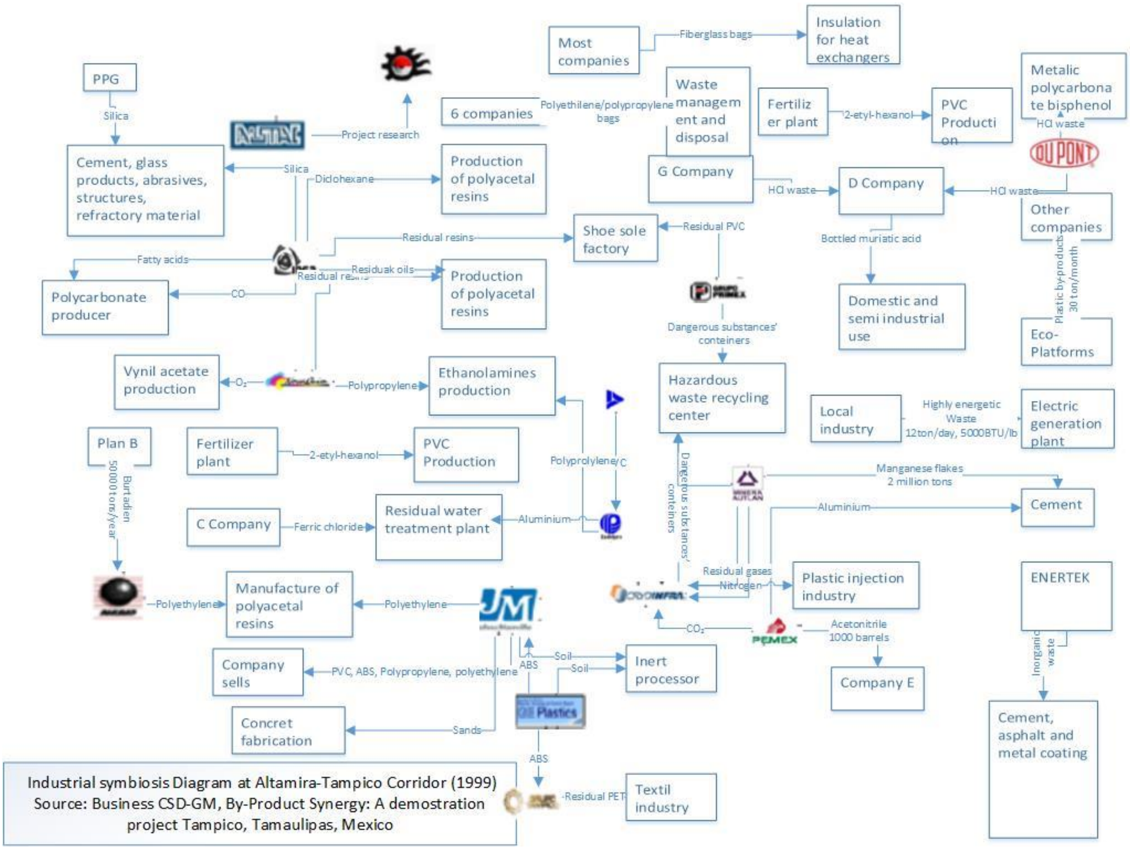
To create a model for the dynamics of industrial symbiosis, which takes a comprehensive overview of its organization process, we require a methodology that combines the outcome of several research approaches. In what follows, we refer to the following approaches: 1) the biophysical approach (identifying and accounting for the energy and material flow changes in the industrial symbiosis relationships in an ecosystem); 2) the social dynamic approach (based on the authors' literature review, and interviews with public authorities, civil society, and research and education organizations). The methodology is applied to the Altamira Industrial Symbiosis case study, and underlines its potential application to other industrial symbiosis cases for analyzing the historical organizational process that influences the present situation and structure of the network.

Biophysical approach

In the phase started in 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 (Figure 37) was created to improve material and energy flow accounting.

The following diagram (Figure 37) was the only available model of BPS Altamira, and every company was taken as a black box. The internal processes were 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 et al., (2010). 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, 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 Synergic Diagrams, depicting existing synergies and proposing further potential synergies.

Figure 37. Material and energy flow diagram created from information provided by the WBCSD



Source: (Lule Chable, Cervantes Torre-Marin, & Carrillo González, 2013)

A regional diagnostic was made with secondary sources and official data to identify the industrial dimension and AISTAC's influence during phase 2. The role of the AISTAC was documented by interviewing some members and identifying the existing and potential mechanisms of cooperation.

Social approach

To gather the qualitative data that shed light on the social 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 provide 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 the political, cultural, ecological, and economic dimensions.

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 multi-phase model of the BPS Altamira project into an overall model, encompassing economic, social, and environmental dimensions. Without the understanding gained from looking back at the history of stakeholders and regions, it could soon become the most tangible example of an inarticulate structure of variables and resources, acting in the short-run and trying to solve problems in day-to-day planning.

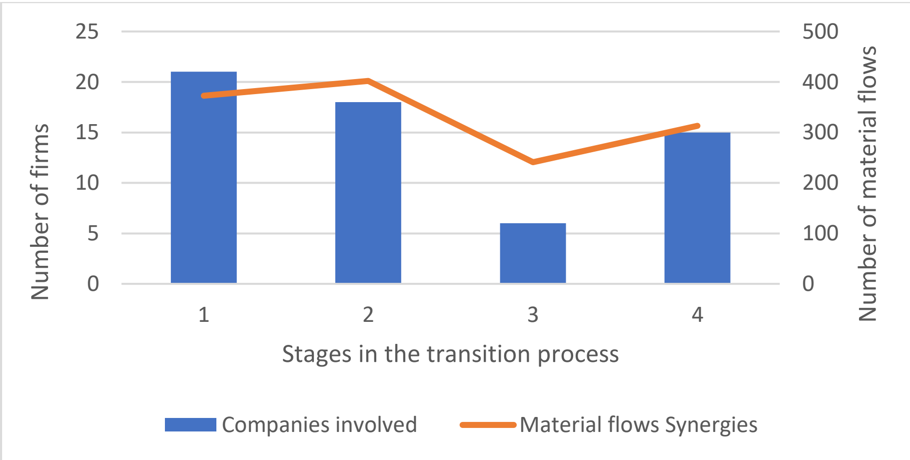
We are confident that the identification of motivations, key actors and factors, and the overall history for each IS would expand the expected benefits from a dynamic, multidimensional understanding of industrial symbiosis, and would ensure the success of the succeeding phases, providing potential organizational strategies, according to the phase of development of the industrial symbiosis, instead of only "end of pipe" solutions based on technology efficiency to partially solve problems.

RESULTS AND DISCUSSION

We aim to depict the benefits obtained from a comprehensive transitional process analysis for Industrial Symbiosis, defining for this purpose 3 different phases - regional efficiency, regional learning, and sustainable industrial district (Baas and Boons, 2004) - and relating them to an underpinning motivation linked to the starting actors, which interacts in the overall history of the ISN. Our understanding of the ISD 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 encompass a compelling interactive learning process.

From Figure 38, we can corroborate that from phase 2, when the marginal efficiency tipping point is reached, the number of firms involved and the number of material byproduct flows in the Industrial Symbiosis decreased with time up to phase 3. According to the data obtained in the interviews, this effect was triggered by the decreasing marginal efficiency of synergic investments. The previously mentioned marginal efficiency reduction reduces the attractiveness of the symbiosis, combining with the fact that the Altamira BPS Industrial Symbiosis is based only on ancillary processes in the petrochemical industry. Phase 4 is a tipping point when the Altamira municipal government contributes to the development of a strategy for the development of an Eco-cluster. The Eco-cluster includes small and medium size firms as potential stakeholders of the eco-innovative strategies, increasing the synergetic material flows concerned.

Figure 38. Historical transition process in Industrial Symbiosis



Relevant insights were developed, that allowed us to understand what are the mechanisms which determine the attractiveness 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 in social and biophysical dimensions. In the social dimension we found the size of the enterprise, cost criteria, shared language (facilitating communication), organizational skills, environmental values (respect, cooperation, ethic and social responsibility), trust in relevant structures, and environmental policies and regulations in Mexico. In the biophysical dimension, we found technical resources, available technology, and availability of by-products in the ISN (Cervantes, 2013b).

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.

The company size was a determining factor: only large, and occasionally medium-sized companies, could make long-term investments.

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.

Cost criteria: It was clear at the beginning that the 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.

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 counted on the properties required for the 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 project participants to move forward in a modernization process or technological adaptation. Projects failed because their byproducts did not match the required technical specifications.

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.

Environmental policies and regulations in Mexico: these were the largest obstacles to synergy consolidation because of the highly 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 Industrial Symbiosis approach as a process for innovation is not a perfect model, but rather an ecosystem in which inter-relationships between different sub-ecosystems have been split into human activities and plans. To imagine a sustainable industry, we need to go beyond input and output flows (the study of metabolism), 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) in a sustainable way to reduce the amount of inputs that industry requires for their production processes.

Industrial Symbiosis is a sustainability related approach and 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.

CONCLUSION

While Industrial Symbiosis may not be a perfect model (e.g. Kalundborg), it can be an ecosystem in which inter-relationships propose cooperation sharing spaces with competition, and in which environmental, social, and cultural dimensions improve the diagnosis of a local industrial ecosystem. This historical analysis and description of the symbiotic trajectory, considering social and economic aspects of the Tampico-Altamira experience shows that a petrochemical industrial ecosystem building the symbiosis around ancillary processes and gravitating around a couple of central firms, achieve the marginal efficiency tipping point in the Regional efficiency stage.

According to the historical analysis, some innovative strategies could be proposed foster employment and by-product exchange dynamism, like an eco-innovative ecosystem strategy, encompassing small and medium size firms for territorial attractiveness. The empowerment of new startups is opening new business opportunities in the information and technology sector, 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 an historical analysis of the industrial symbiosis process is highly recommended, especially because it is facing multidimensional social processes (interfirm, intrafirm and territorial). This kind of systemic and dynamic analysis provides a better understanding of the feedbacks and driver mechanisms involved in the industrial ecosystem, firm participation/membership, incorporating values and communication skills. This analysis could be replicated in other industrial symbiosis networks, becoming the sustainability streamline for a new business model, encompassing a kind of socio-ecological strategy which has the potential to significantly reduce the ecological impact of the industrial processes of large corporations.

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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.

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SECTION IV – CASE STUDIES

CHAPTER 6. ALTAMIRA'S UNDERSTANDING OF THE TERRITORIAL CONTEXT THROUGH ECO-EFFICIENCY AND RESILIENCE

Industrial symbiosis's innovative approach based on circularity, resilience and efficiency collaboration: the Altamira symbiosis experience

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ABSTRACT

Industrial Symbiosis (IS) is a social innovation strategy in the field of industrial ecosystem cooperation that aims to enhance industrial organizational sustainability through circular economy principles. The pursuit of circular viability entails the integration of resilience into the industrial ecosystem, as a mechanism to reduce the problem of individual efficiency objectives, to result in a long-term sustainability increase, even if in the short-term efficiency is slightly reduced. The idea of cascading synergies between firms offered by industrial symbiosis, in which cheap available waste is used becomes controversial in a waste-based economic model. A successful market-based model that would lead to waste production, responding to the market's constraints, seems troublesome. The idea of an integrated model, which includes resilience as a goal and input-output exchanges controller, makes sense in the circular economy theoretical framework. The Altamira Industrial Symbiosis experience confirms this hypothesis. At Altamira, where only two of the nine firms in the symbiosis receive benefits from the symbiosis, and in which an uneven relationship between resilience and efficiency was shown for almost every firm, the stakeholders acknowledge the negative effects of the lack of collective resilience on the industrial symbiosis.

Keywords: Circularity, viability, Altamira, industrial ecosystem, eco-efficiency, resilience

HIGHLIGHTS

- Circular viability as a comprehensive strategy embedded in circular economy;
- Resilience as condition to maximize efficiency in the industrial symbiosis;
- Altamira case study confirms that eco-efficiency alone, gives negative trade-offs to network sustainability;
- IS can provide the incentives to maximize firm's eco-efficiency through the integration of resilience in the investment mix;

INTRODUCTION

Since the beginning of the IE conceptualization, it entails a holistic and systemic relationship with the biosphere, establishing a metaphor with the ecological ecosystems dynamics. Considering firms as organisms exchanging material and energy within them and with the environment. In this metaphor, the industry represents a semi-closed ecosystem where material and energy flows should be reincorporated in the system throughout a circular logic. Although many experiences of industrial ecology have been implemented around the world since the beginning of the 20th century, the number of success stories is still very small. The implementation of industrial ecology into a specific territory faces many hindrances, related to technical, economic, informational, organizational, infrastructural, or legislative areas (Duret, 2007).

In this paper, we define Industrial symbiosis (IS) as an organizational strategy, which is a sub-field of industrial ecology, and which aims to solve some of the main obstacles faced by industrial ecology. In that sense, we are going beyond the definition proposed by (Chertow, 2000) which highlights the technical and biophysical aspects. We are convinced that human dimension is essential for the understanding of industrial symbiosis as a social process, based on ecological, political, cultural, and economic aspects. A relatively small, but compelling set of examples of Industrial Symbiosis has been described in the American continent like the Industrial ecology platform in Sorel-Tracy, Burnside and Halifax, all of them in Canada (Duret, 2007), the Biorefinery symbiosis in USA (Realff & Abbas, 2004), Chelsea, Springfield, Devens and Durham Eco Industrial Park in the USA (Duret, 2007). Tthe Agricultural symbiosis (Ometto, Ramos, & Lombardi, 2007) and Biorafinery symbiosis (Santos & Magrini, 2018) both of them in Brazil are also evidence of this experiences in the American continent.

Inspired by the previous iconic examples two problems have been identified in industrial symbiosis (Duret, 2007) (Orée, 2013). The first problem is the inefficient internal use of materials, energy, and information. Industrial Symbiosis, like any other network of organizations, faces the competition and efficiency requirements of the market. Any inefficient use of resources could put in danger the stability and utility of every firm, which would be enough to interrupt the symbiotic flows or, in the worst, case cause a withdrawal from the IS. The second problem is the lack of resilience to external perturbations (Ruth & Davidsdottir, 2009), which negatively affect the benefits (economic, environmental, and political) arising from the IS.

The current debates highlight the circular viability (efficiency/resilience), addresses in our conceptual framework (Diemer, Morales, 2016) which displays a strong relationship between resilience and efficiency in the long-term sustainability of industrial symbiosis. Circular viability is not an isolated concept; it is one of the four theoretical axes to accomplish sustainable transition in an industrial ecosystem. Consumption and production in circular economy happen together, but can be disaggregated only for analytical purposes.

This paper does not aim to provide an exhaustive literature review on industrial symbiosis but to gather some fundamental insights into the relationship between efficiency and resilience. The Altamira case study provides an excellent base for investigation in a developing country, with an existing literature about the territorial embeddedness, coming from the institutional, organizational and historical process of industrial symbiosis (Morales M. , Diemer, Cervantes, & Graciela, 2019). Altamira encompasses some features that also seem to facilitate the connections between stakeholders, and the collaboration in the network, such as the seaport location and the relevant role played by the Business Association.

The aim of this study, based on the results obtained in Altamira, is to test the assumption that industrial symbiosis is a social innovative strategy that could integrate resilience into the efficiency equation attempting to improve sustainability in the industrial ecosystem. To measure resilience and efficiency in industrial symbiosis several assessment methods have been used. To the best of our knowledge, previous studies on the sustainability of IS have analyzed IS in terms of resilience or eco-efficiency, but not through both aspects, see (Fraccascia, Giannoccaro, & Albino, 2017) and (Yazan, Romano, & Albino, 2016).

The method for evaluating circular viability in IS (Diemer, Morales, 2016) (Morales M. , Diemer, Cervantes, & Graciela, 2019) combines MEF, Economic Analysis (EA), and Resilience impact with a coherent narrative to check if in the Altamira Industrial Symbiosis, efficiency does, or does not, always bring resilience. The maximization of efficiency and resilience does not come naturally, and a holistic and comprehensive strategy should be enterprise to promote circularity, by borrowing insights from studies in others disciplines. The data used in this paper comes from both primary and secondary sources. The secondary sources include academic literature reviews as well as practitioner and public authority reports, such as the WBCSD-Gulf of Mexico and the AISTAC. The primary sources are a set of interviews conducted with corporate managers, as well as with local policy makers, expert analysts and members of directive boards, that are involved in the organizational transition process and know well the specifics of the local petrochemical industry between

December 2016 and March 2017. There were 10 semi-open face-to face interview, enquiring into interactive behaviors, resilience, institutional productive capacity, organizational strategies and byproducts flow exchanges which allowed us understand the qualitative nature of such interdependences. In the Altamira By-product synergies, we show that the pursuit of efficiency is negative if resilience is ignored for the industrial symbiosis's sustainability.

In Section 2, a literature review is devoted to the concept of resilience and efficiency for IS. The methodological tool used to assess efficiency and resilience in industrial symbiosis is shown in Section 3. It includes not only the global biophysical accountancy in the IS, but also disaggregates the byproducts flow for each firm in the industrial network, to demonstrate interdependency. In Section 4, the relative multidimensional (environmental/economic) efficiency assessment in the IS is presented and applied to Altamira IS. In Section 5 the Resilience index (Fraccascia, Giannoccaro, & Albino, 2017) is applied to Altamira IS, and the steam, wastewater, waste oil, paper, plastic, sludge, and CO_2 exchanges are described. In Section 6 the IS resilience index and the relative eco-efficiency analysis are presented and applied to Altamira, describing the circular relationship between efficiency and resilience in industrial symbiosis. Conclusions are offered in Section 7.

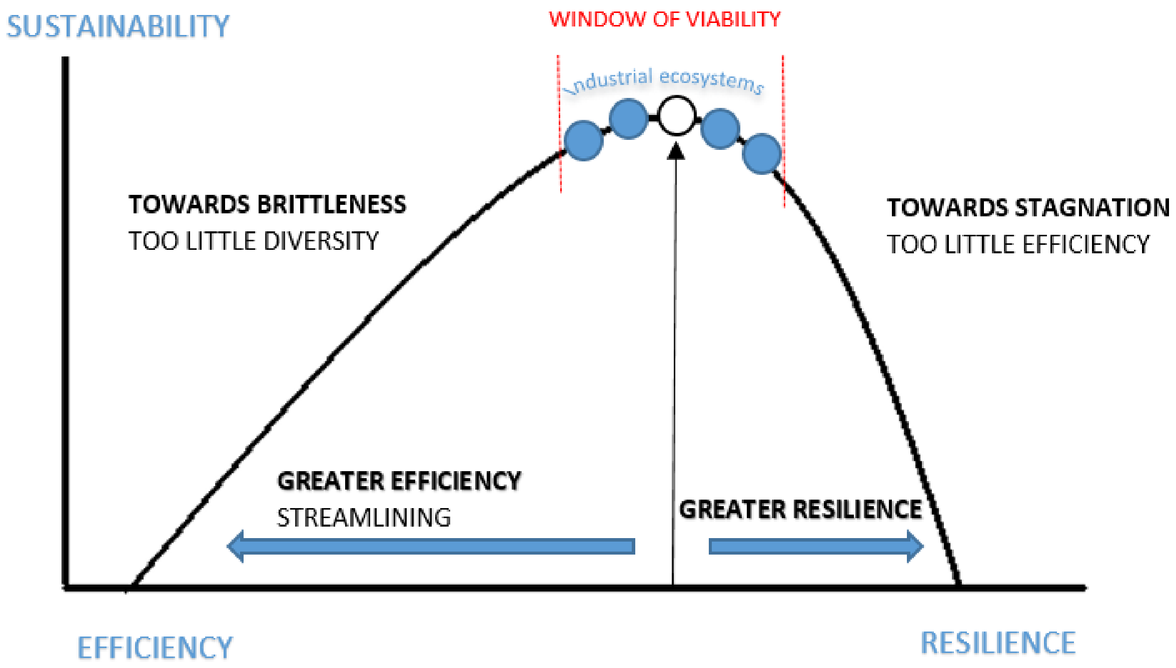
INDUSTRIAL SYMBIOSIS: A LITERATURE REVIEW

The industrial ecology assumptions in this paper propose the existence of four drivers, Governance, Ecosystem interaction, Circular viability, and Scale, (Diemer, Morales, 2016) as the explanatory mechanisms of industrial symbiosis sustainability. In order to meet the aims of this paper we develop the circular viability analysis (efficiency/resilience). Some relevant questions are posed in this paper, questions like: What is the desirable efficiency and resilience structure for the IS? How can we define the efficiency limit in the IS? What does IS bring to the individual firms and to the network? What is the individual firm bringing to the IS? These questions are presented here as insights to be answered in future research projects.

The diversity of stakeholders' motivations and values in the industrial ecosystem, the conflicts of interests and the adaptation time lags, push the industrial symbiosis to move away from sustainability if there is no strategical steering. In IS, firms depend on each other's waste to function, if they grow, they will increase input demand from other firms, meaning more waste demand. But, if firms are trying to maximize efficiency at the individual firm level (micro-efficiency), the amount of waste they produce is reduced, and so reduces the growth possibility for the other firms which depend on those wastes for production. For example, in the Altamira IS, CABOT depends on INSA's wastewater. To improve individual throughput CABOT wants to maximize wastewater inflows, but INSA wants to minimize it. This is a paradox - what seems to be a benefit from a micro-efficiency point of view, ends up as a macro-efficiency disadvantage (Costa & Ferrão, 2010), which also has negative spillover effects for the firms that use by-products as inputs. Cooperation in the IS may result in a reduction of individual efficiency, but result in a long-term collective benefit in resilience.

One of our main assumptions is that encouraging industrial symbiosis and synergies, beyond the individual firms, is sustainable, as mentioned by (Mirata, Experiences from early stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges, 2004) and (Zhu, Lowe, Wei, & Barnes, 2007), and it encourages social resilience in the industrial ecosystem. We also assume in this paper that sustainability is achievable in the industrial symbiosis, even if the individual firms have short term reductions in efficiency. The long-term outcome has not been analyzed in the IS, so the feedback effects of efficiency decrease cannot be taken fully into account even if theoretically incorporated in the analysis.

Figure 39. Window of circular viability in the quest of Sustainability



Source: Taken from Goerner, Sally, & Voller, Randolph. (2013). Rebuilding Economic Vitality – R.E.V. (Ellen MacArthur Foundation, 2013) *and modified by the authors.*

This article provides a critical outlook of industrial symbiosis as a tandem, encompassing efficiency and resilience. First, efficiency and its connection to the industrial metabolism, looks at material, energy, and monetary flows from environmental and economic points of view. Second, industrial symbiosis' resilience, highlights firms' diversity and waste's ubiquity in IS, followed by an analysis using the impact index of the disruptive events caused by the withdrawal of a firm. We describe the resilience and efficiency state of the symbiotic network to understand the resilience and efficiency relationship in industrial production, based on the data collected from stakeholders at the Altamira IS in 2017.

UNDERSTANDING THE ECO-EFFICIENCY OF INDUSTRIAL SYMBIOSIS

The efficiency of industrial symbiosis is understood as the average measure of the individual firm production efficiency gains derived from the existence of the IS. The concept of efficiency at industrial symbiosis is expressed by the relationship between the product and its inputs, measured in the physical units of output compared to the physical units of inputs (Valderrama, Neme, & Ríos, 2015). The eco-efficiency can be measured by a relationship that takes into account economy and ecology (Huppes & Ishikawa, 2005) . Taking into account the underpinning environmental impact, which according to (Boiral, Concilier environnement et compétitivité, ou la quete de l'éco-efficience , 2005) comes not only from legislation, but also from the internal pressures of civil society, and the economic and competitive constraints that limit the non-productive investments. This can be expressed in the following equation.

Equation 1. Eco-efficiency calculation

$$\text{Eco-efficiency} = \frac{\text{Environmental cost or value}}{\text{Environmental impact}}$$

Following the literature on green investment efficiency (Olivier , 2005) we can show that the efficiency curve for the industrial symbiosis network reaches a tipping point, when there is a marginal reduction. According to the WBCSD-Gulf of Mexico (2006), efficiency means generating more value with less impact[22] (Verfaille & Bidwell, 2000). Incremental research on industrial symbiosis' efficiency has predominated until now, but it is unreliable when comparing long-term behaviors in industry, so the development of a radical innovation research entailing a holistic and systemic approach in economic, ecological, cultural, and political dimension seems to be crucial (Vanalle, Moreira, & Lucato, 2014) (World Business Council for Sustainable Development, 2006). In the past, the literature has mainly focused on industry-specific determinants of efficiency, to understand the efforts made by manufacturing industry (Valderrama, Neme, & Ríos, 2015) (Pearce, 2008). However, the adoption of a broader perspective is required to develop the idea of efficiency as a wider parameter, which can simultaneously measure economic and environmental performance.

[22] (Huppes & Ishikawa, 2005) distinguish four types of eco-efficiency. The first two are environmental productivity and its inverse, environmental intensity of production, referring to the realm of production. The second two, environmental improvement cost and its inverse, environmental cost-effectiveness, are defined from an environmental improvement measures point of view.

UNDERSTANDING RESILIENCE IN INDUSTRIAL SYMBIOSIS

Resilience was introduced to the ecological literature by (Holling, 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 study resilience is used through its dynamic definition as "the capability of a system to absorb disruption[23] and reorganize while keeping essentially the same structure, function, drivers and flows".

Systems' resilience depends on the system's structural diversity and ubiquity. The characterization of diversity lays on the number of *different functions* performed within a system, and the number of *different responses* to environmental changes. Redundancy is the number of species that perform the same function. If a species with big ecological impact is removed, the consequences for the system may be more critical than if a species with smaller ecological impact is removed (Walker B. , 1992). Social systems' resilience has become a target in almost all dynamic processes, see (Barbault, 2013), (Juvin, 2013) and (Martin S. , 2005). Resilience has received a lot of attention through a dynamic and systematic approach in different fields, such as risk management (Dauphiné, Provitolo, & Colin, 2007), climate change (Bériot, 2013), urban resilience (Laganier, 2013), and territorial public policy analysis (Dron, 2013).

This paper takes the IS as a complex ecosystem, able to evolve over time, in which the firms correspond to organisms and perform specific functions. These functions foster by-products exchanges, logistics, transportation, and other pooling services between firms. The IS has three main functions: 1) creation of financial benefits for firms (organisms), 2) creation of environmental benefits for the local community (external environment), 3) the generation of ecological benefits for the environment itself.

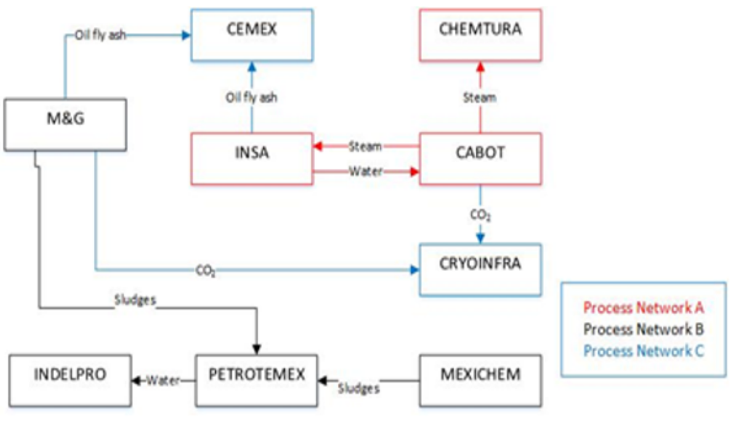
[23] A disruptive event is defined as any event able to affect the feasibility conditions of the IS relationship, altering the current equilibrium state of the IS from a technical, economic, and/or standards point(s) of view (Garner & Keoleian, 1995)

THE ALTAMIRA INDUSTRIAL SYMBIOSIS

The Altamira Industrial Symbiosis (IS) is located in Altamira, Mexico, it has nine firm members; eight multinational firms in the chemical products industrial sector and one cement firm. All of them are large corporations with millions dollars turnover annually. At Altamira IS, by-products are not substituting inputs into the main production process; therefore, the industrial ecology strategies are dominated by ancillary business activities, like cleaning, maintenance, and energy supply to the main production. The secondary role played by the industrial symbiosis in the industrial ecosystem increases the challenge of sustainability, because in the absence of common problems/goals (which usually create dependency), the stakeholders in the system only share on matters which are not strategic for their survival.

As shown in Figure 40, Altamira Industrial Symbiosis in 2016 is presented as by-product synergy network composed by nine firms. To better track the exchanges in the network, we put the exchanges into three different groups - Processes A, B, and C.

Figure 40. Chart of symbiotic exchanges at Altamira



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

Process Network A, in red, is the exchanges between 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. $w_2^1 = 216{,}000\ tons/year$ is delivered to INSA and $w_3^1 = 43{,}200\ ton/year$ to Chemtura.

Process Network B, in black, is the sludge and wastewater exchange 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 $w_1^2 = 900{,}000\ m^3/year$ of wastewater to INDELPRO. M&G Chemicals produces f_2^2 =450,000 tons/year of PET. Mexichem produces f_2^2 =140,000 tons/year of PVC. M&G Chenmicals and Mexichem provide the waste sludge consumed by PETROTEMEX, $w_2^2 = 40\ tons/year$ of sludge waste generated 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 incineration, in a cogeneration system could transform the energy content of sludge into thermal and electrical energy. The main part of the dry matter content of sludge consists of nontoxic organic compounds, so energy recovery is an important alternative for heat generation. The amount of energy that can be obtained depends on the water content, incineration performance, mechanical dewatering, and drying of the sludge (Vatachi, 2016).

Process Network C, in blue, consists of Oil 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 f_1^3 =20,000,000 tons/year, made by INSA[24].

EFFICIENCY'S ROLE IN CIRCULAR VIABILITY

The efficiency of industrial symbiosis, previously defined in the literature, is a good proxy for circular viability, offering a systemic approach that measures the circular stability over time (t) and space (s). Thus, efficiency is calculated in this study in relative terms via two

[24] The amount of CO_2 received as by-product by CRYOINFRA is known, but we do not know the production capacity of that company, information was not revealed because of the secrecy and confidentiality policy.

axes: the consumption process and the production process; by comparing how much extra energy, material, and money a single firm would need if it existed outside the IS.

Any efficiency assessment in industrial symbiosis should include the environmental dimension (material and energy) and the economic dimension, to achieve an accurate description, without disregarding the relevance of the political and cultural dimension, which is not considered in this paper, but will be studied in future research. In this paper, individual efficiency assessment is made firm by firm, by the identification of what they consume and what they produce, in two different scenarios: inside and outside the IS.

ENVIRONMENTAL DIMENSION

The efficiency's environmental dimension consists of materials and energy assessments, which measure the flows within firms in 2016 at the Altamira IS. The main by-product consumers are CABOT, INDELPRO, CRYOINFRA and INSA, together they consume 98% of the total by-product material inflows, which is more than 1.9 million tons a year. The main material exchanged is the wastewater, ranking CABOT and INDELPRO in first and second place. Regarding material production, the four firms who produce 100% of by-products at Altamira are INSA, PETROTEMEX, CABOT and M&G Chemicals, which means industrial ecosystem, is based on wastewater, steam, and CO_2 exchanges.

The consumers are different from the producers. Two of the by-product consumers, INDELPRO and CRYOINFRA are not represented on the IS material consumption flow list. Chemtura, CEMEX and MEXICHEM are not taking advantage of the by-product material supply in the IS, even if CEMEX has a large fly-ash consumption potential, but M&G Chemical's and INSA's production capacity (2 tons/year each) is marginal in comparison with CEMEX's needs. This is a missed synergy opportunity, which is becoming a standard practice in the cement industry. CABOT, INSA and INDELPRO get the main material synergies advantages in the IS.

Energy has been approached only in an exploratory way, by looking at the energy use inflows, in terms of calorific content. Steam and sludge have an energy per unit throughput, and to standardize the energy units we use Kilocalories (Kcal). The energy consumption at the IS includes only INSA and Chemtura, which use steam and sludge as energy sources for their processes. The calorific value of steam is 510 Kcal/kg at the entrance and 475 Kcal/kg at the exit of the gas duct (Forbes Marshall, 2014), giving a consumption of 475,000 Kcal/ton of calorific power in the Altamira IS.

The Altamira IS consumes more than 123,000 Giga calories a year. The only significant energy by-product producer is CABOT. Even when the IS reaches more than 132,000 Giga calories a year, the only two companies which consume by-product energy are INSA and Chemtura. The difference between energy production and energy consumption is only 7% of total energy produced in the IS (Lule & Cervantes, 2010).

ECONOMIC DIMENSION

Economic assessments can be presented in two ways: 1) quantitative measure of micro and macro-performance; 2) qualitative measure of collective performance (Aurez & Georgeault, 2016). According to the economic analysis, the monetary motivation is essential at Altamira, and fosters relationships between government, industry, and other institutions. We argue that the economic dimension is not well represented by static monetary analysis, because the economic activity is also influenced by past and current behaviors and steer of technological change (Laurens, Le Bas, Lhuillery, & Schoen, 2016), and public regulation. Developed from an environmental management perspective, the idea is to establish the most efficient strategy for contributing to the accomplishment of circular economy, based on the use of what used to be widely available and inexpensive materials. However, a big increase in the use of this waste could became a problem because they are not commodities in the strict sense; their production relies on the production capacity of the main product. They cannot be seen as commodities, because their economic viability depends on the reduction of production costs due to the position of the by-product, in respect to the central production process. If the by-product turns into main product, then the cost composition changes and it becomes economically non-viable. Therefore, an increase in the demand for a by-product needs an underpinning increase in the main product demand, otherwise the IS's demand is not supplied and uncertainty rises in the symbiosis. Therefore, one main reason of limited emergence of Industrial Symbioses worldwide is the risk in by-products regular supply, which depends on the firms' main production volumes. So, we propose a balanced industrial symbiosis strategy which provides a social innovative answer for stock optimization and consumption (Aurez & Georgeault, 2016).

Table 12. Altamira IS financial By-products substitution assessments

Firms	By-product used	Quantity used	Units	Unit price (USD)	By-products substitution cost (USD)
CABOT	Wastewater	950,000	m^3/year	$0.34	$326,800
INSA	Natural gas	2,754	ton/year	$89.16	$245,326
INDELPRO	Wastewater	450,000	m^3/year	$0.34	$154,575
CRYOINFRA	CO_2	315,000	ton/year	$0.17	$54,117
Chemtura	Natural gas	551	ton/year	$89.08	$49.065
CEMEX	Oil fly ash	4	ton/year	$1,204.43	$4.818
PETROTEMEX	Natural gas	4	ton/year	$89.08	$372
TOTAL					**$835.074**

Note: 1. Units in US dollars at the exchange rate of May 22, (Bank of Mexico, 2017)

2. Water costs determined by the hydrological basin where Altamira is situated (CONAGUA, 2016).

The chemical industry in Mexico has an average efficiency of 0.717 (Valderrama, Neme, & Ríos, 2015). Due to participation in the industrial symbiosis, INSA and Chemtura have an efficiency gain of 1.97% and 0.31% respectively, which means an efficiency of 0.731 for INSA and 0.719 for Chemtura.

After a cost/benefit analysis, we conclude that CABOT is the company with the biggest financial benefits, US$320,000 per year, followed by INSA with US$245,000; the firms that get almost no financial benefit from these synergies are M&G Chemicals, Mexichem and Petrotemex. The efficiency gain at the IS is calculated using the relative efficiency of every firm in the IS, the indicator includes environmental and economic efficiency in the industrial symbiosis.

ECO-EFFICIENCY INDEX

The efficiency index has environmental and economic dimensions. The environmental dimension is composed of material and energy parts; financial savings and efficiency make up the economic dimension. The economic dimension measures the difference of the industrial symbiosis scenario from the average performance of the industrial sector. For a better understanding of the equation and the underpinning relationship with resilience, the data is organized in two different axes, consumption and production. The equation is:

Equation 2. Efficiency consumption and production

$$e_i^C = \frac{[M_C + E_C]}{4} + \frac{t}{2} \qquad e_i^P = \frac{[M_P + E_P]}{4} + \frac{s}{2}$$

The consumption efficiency (e_i^C) consists of the use of material consumption (M_C) plus the energy consumption (E_C) plus efficiency consumption (t). In order to give the environmental ($M_C + E_C$) and economic (t) dimensions the same worth in the formula (in line with the theoretical framework), we divide by four on the left because we have the sum of two values, and in the right with only one value, is divide by two. The production efficiency (e_i^P) has the same composition, with the material production (M_P) and the energy production (E_P) divided by four and the substitution cost (s) value by two.

Equation 3. Efficiency assessment

$$ee_i = e_i^C + e_i^P$$

The consumption efficiency (e_i^C) and the production efficiency (e_i^P) index compose the efficiency index, encompassing the economic and environmental dimensions within the industrial symbiosis strategy. The firm that obtains the highest benefits in efficiency from its participation in the IS is INSA with 40%, followed by CABOT with 37%. Overall, the Altamira IS shows a high degree of efficiency concentration, giving benefits to only two firms. This can be explained in part because of their multiple interconnections developed in the symbiosis, and because they were the founding members in the network, with a long history of cooperation, which has triggered formal and informal communication, social connections, reciprocity, and trust.

RESILIENCE'S ROLE IN THE I.S.'S CIRCULAR VIABILITY

Based on stock optimization, the IS's efficiency limits encounter resilience constraints, because firms depend on each other's waste to function. If they want to grow, assuming that most firms are trying to maximize efficiency beyond the firm's individual tipping point[25], the amount of waste they produce will determine the possibility of other firms to grow. In this section we analyze resilience, defining firm diversity, and waste ubiquity; then we analyze the Altamira IS case study, using the resilience impact index, which consists of analyzing a firm's withdrawal based on the methodology developed by (Fraccascia, Giannoccaro, & Albino, 2017) (Schiller, Penn, & Basson, 2014), where we identify some advantages in comparison to the material network analysis. Finally, we validate the consistency of the resilience index with the conceptual framework, organizing the IS features in three groups: 1) firms that produce waste, 2) wastes exchanged and 3) firms that use the wastes as inputs.

Production (P) is an $f\ x\ w$ matrix that replicates the *wastes production structure*: the generic element P_{ij} denotes the amount of waste *j* produced by firm *i* and exchanged within the IS. Similarly, Consumption (C) is an $f\ x\ w$ matrix that replicates the *waste use structure*: the generic element C_{ij} denotes the amount of waste *j* used by firm *i* as the result of symbiotic exchanges within the IS. We define diversity as the number of wastes exchanged between firms and firms production diversity as the sum of each waste produced by the firm. We understand the waste index as the amount of wastes produced within the IS, and firms diversity $D_i^P = \sum_{j\,|\,P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}}$ as the sum of the ratios between the amount of each waste produced by *i* and the amount of that waste produced within the IS.

We define ubiquity as the number of firms that produce and consume each waste exchanged within the IS. Ubiquity is associated with two ubiquity indices: 1) ubiquity in production

[25] Firm's individual tipping point is the point where each firm reaches the declining marginal growth point in the efficiency normal curve, leading to the stagnation of efficiency.

$U_j^P = \sum_{i=1}^{f} p_{ij}$ where $\begin{cases} p_{ij} &= 1 \; if \; Pij > 0 \\ p_{ij} &= 0 \; if \; Pij = 0 \end{cases}$ defined as the number of firms that produce the waste, 2) ubiquity in consumption $U_j^C = \sum_{i=1}^{f} C_{ij}$ where $\begin{cases} c_{ij} &= 1 \; if \; Cij > 0 \\ c_{ij} &= 0 \; if \; Cij = 0 \end{cases}$ defined as the number of firms that use the waste. To calculate our indices, we defined the IS waste production (P matrix) and the waste consumption (C matrix). For each firm and for each waste, the diversity indices and the ubiquity indices were calculated (last row and column of Tables 13 and 14).

Table 13. Waste production by firms in Altamira

Waste production by firm in Altamira	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	**1.7063**
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**
CEMEX	0	0	0	0	0	**0**
CHEMTURA	0	0	0	0	0	**0**
INDELPRO	0	0	0	0	0	**0**
Waste ubiquity index (U^P)	**1**	**2**	**2**	**2**	**2**	

The Altamira IS involves nine firms (f=9) exchanging five different wastes (w=5). Figure 40 shows the waste exchanges within the IS. Table 13 shows production, and Table 14 consumption. The firms produce on average two different wastes and use only one waste. The firm diversity index ranges from 0 to 1.7063 for production and from 0 to 1 for consumption. On average, 1.8 firms produce each waste, every waste is produced by 2 firms except for steam (only produced by CABOT); and 1.4 firms use each waste, as depicted in the waste ubiquity index in Table 14. For production, the waste ubiquity is 1 for steam and

2 for other wastes. In consumption, steam and wastewater have ubiquity of 2, and other wastes (oil fly ash, sludge and carbon dioxide) of 1.

Table 14. Waste consumption by firm in Altamira

Waste consumption by firm in Altamira	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**
INSA	216,000	0	0	0	0	**0.8333**
PETROTEMEX	0	0	0	70	0	**1**
MEXICHEM	0	0	0	0	0	**0**
CRYOINFRA	0	0	0	0	315	**1**
CEMEX	0	0	4	0	0	**1**
CHEMTURA	43,200	0	0	0	0	**0.1666**
INDELPRO	0	450,000	0	0	0	**0.3214**
Waste ubiquity index (U^c)	**2**	**2**	**1**	**1**	**1**	

As a result of a disruptive event consisting of the withdrawal of a firm *i,* we define the following two impact indices, bringing some insight from previous resilience studies in Industrial Symbiosis see (Fraccascia, Giannoccaro, & Albino, 2017) :

Equation 4. Impact indexes formula

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

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

Where P stands for production and C stands for the consumption, $\overrightarrow{d_\iota^P}$ and $\overrightarrow{d_\iota^C}$ are the 1 x *w* vectors. Hence, these vectors refer to the diversity of firms *i* in waste production and waste consumption respectively. $U^{P^{-1}}$ and $U^{C^{-1}}$ are the inverse of ubiquity for each waste produced and used in every firm, $\vec{\alpha}$ is the 1 x w vector having all elements equal to one, introduced to obtain a scale value for our indices.

Table 15 shows the resilience index calculated for each firm, and ranges from 0.6956 to 0.9833. CABOT, PETROTEMEX and INSA are the most critical firms in case of disruptive events.

Equation 5. Resilience assessment index

$$\rho_i = 1 - (\iota_i^P + \iota_i^C)$$

The resilience index captures the impact of a firm's withdrawal with a high diversity function, for example, the removal of CABOT is more critical than the withdrawal of M&G Chemicals. The resilience index is obtained subtracting the aggregated value of 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 ubiquity and diversity of wastes exchanged. Even if M&G Chemicals stops the sludge exchange, CO_2, and Oil fly ash exchange would continue because Mexichem, INSA, and CABOT would continue to produce it. This correctly shows that the IS is more resilient to a disruptive event happening at M&G Chemicals than a disruptive event taking place at CABOT. CABOT exchanges steam, which is a low ubiquity waste. Since steam is produced only by CABOT and presents low ubiquity, the "exchange steam" function would be lost, if CABOT leaves the IS.

Table 15. Resilience (ρ_i is highlighted in bold), impact measures in Altamira

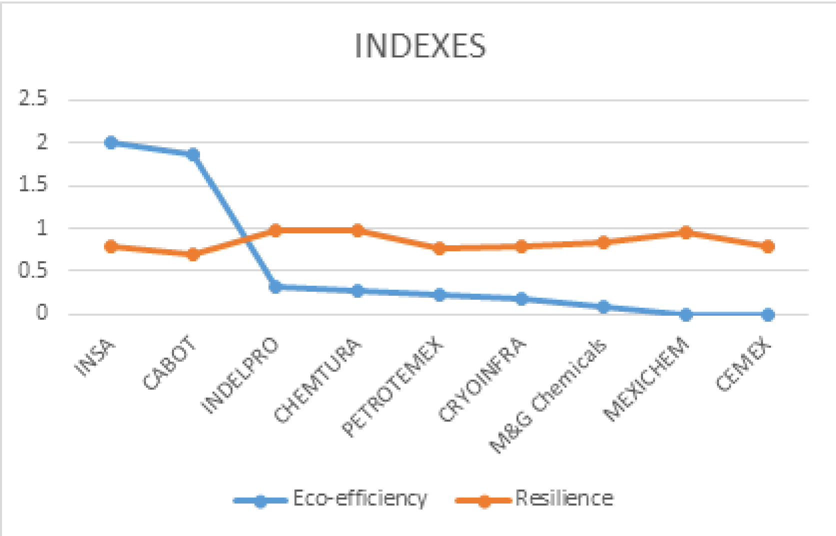
	Resilience index		
	ι_i^P	ι_i^C	ϱ_i
CABOT	0.2365	0.0679	**0.6956**
M&G Chemicals	0.1706	0	**0.8294**
INSA	0.1179	0.0833	**0.7988**
PETROTEMEX	0.0321	0.2	**0.7679**
MEXICHEM	0.0429	0	**0.9571**
CRYOINFRA	0	0.2	**0.8**

CEMEX	0	0.2	**0.8**
CHEMTURA	0	0.0167	**0.9833**
INDELPRO	0	0.0321	**0.9679**

DISCUSSION AND RESULTS ON CIRCULAR VIABILITY

This study tries to integrate resilience into the social industrial ecosystem. Eco-efficiency projects usually disregards resilience spillover; turning away from the industrial symbiosis endeavor and moving to a linear logic, which brings a risky behavior to every collaborative decision, because the systemic approach is set aside.

Figure 41. Efficiency and resilience index from the Altamira IS case study in 2016



In this diagram, we show production efficiency and resilience in 2016 for Altamira IS. The eco-efficiency (blue line) determines the system's ability to maximize throughput, and the resilience (yellow line) depends on the system's capacity to allow for divergent processes, by maintaining a degree of freedom that increases resilience. The horizontal axis represents all the firms in the Altamira IS, so the best circular viability performance is achieved by firms 1 (INSA) and 2 (CABOT), which build collaborative resilience and efficiency, and keep the resilience threshold above a minimum. The more resilience is taken into account in the decision-making, the better efficiency is achieved in the circular viability of industrial symbiosis.

The findings looks forward to encourage stakeholders to believe that industrial symbiosis self-regulates the industrial ecosystem, with resilience cutting the risky over-efficient behavior without a biophysical ceiling, determined by the collaborative input/output exchange. This leads to a transition from a traditional firm perspective to an industrial symbiosis perspective, already suggested by (Meneghetti & Nardin, 2012). Following this approach, problems can be solved at an aggregated level, and optimizations not otherwise achievable, can be performed through solution centralization due to geographical and organizational proximity (Boutillier, Laperche, & Uzunidis, 2015).

In the Altamira IS, CABOT is the second most efficient firm, and at the same time it ranks second in vulnerability. This means that an IS should be strategically steering to strengthen both efficiency and resilience, because it does not happen naturally, as shown in the Altamira by-products synergy.

Table 16. Firms' Efficiency and Resilience index in Altamira IS

	Efficiency index	Resilience index
INSA	2.00	0.80
CABOT	1.87	0.70
INDELPRO	0.32	0.97
CHEMTURA	0.28	0.98
PETROTEMEX	0.23	0.77
CRYOINFRA	0.19	0.80
M&G Chemicals	0.10	0.83
MEXICHEM	0	0.96
CEMEX	0	0.80

The analysis of the trade-off between resilience and efficiency paves the way for a better understanding about how to improve circularity in industrial ecosystems. The higher the relative cost for efficiency investments, the more attractive to invest in resilience projects. However, efficiency and resilience are not only substitutable, but also complementary. To enhance circular viability, both efficiency and resilience are necessary, opening the way to efficiency maximization only when the threshold of resilience is preserved in the system. Recent research on the circular economy about complex flows and stocks (Aurez & Georgeault, 2016) (Ruth & Davidsdottir, 2009) support our findings based on two statements. First, IS requires resilience, i.e. the capacity to choose alternative paths to pursue its goal in case of crisis. Second, IS requires economy of scale, i.e. the capacity to process larger amounts of energy thus reducing overheads. Increases in resilience and efficiency depend on shared flexibility and control. Circular viability targets more than just economic issues, highlighting the need for holistic approaches that internalize resilience and provide the optimal allocation of resources.

The strategy to promote complementary efficiency and resilience entails a systemic analysis of middle- and long-term investment decisions, encompassing the suppliers and clients diversity and ubiquity analysis, since where the higher the efficiency in reducing waste, the lower the amount of by-products available to be shared. Therefore, the synergy between CABOT and INSA, embedded in the Altamira IS illustrates very well this strategy, establishing that the greater the amount of residual steam available as input, the greater the demand by INSA up to a threshold. This threshold represents the tipping point where the full productive installed capacity is attained, after that if a further increase in the steam supplied from CABOT is desired, the underpinning increase in the installed capacity needs to be programmed in the long term, if not the extra by-product has zero value, because it is not usable.

CONCLUSIONS

Industrial symbiosis can steer a social innovation strategy to give circularity to industrial processes in the context of an industrial ecosystem, entailing efficiency and resilience assessments. The Altamira case study in Mexico suggests that firms' productivity could be improved when they are embedded in an industrial symbiosis. The data obtained in 2017 from the case study validates the relationship between efficiency and resilience, arguing that the IS should be strategically structured to strengthen collaborative efficiency and resilience.

The integration of resilience into the system understanding seeks to reduce the firms' individual efficiency objectives through collaborative exchange. Industrial symbiosis aims to scale up territorial social/biophysical approaches that guarantee resilience and efficiency practices, triggering strategies with the aim of restoring social balance.

There is a high degree of efficiency and centralization in Altamira IS, where only three firms compose the core of the industrial symbiosis (CABOT, INSA and INDELPRO). The interdisciplinary analysis of Altamira IS shows that resetting circular production is possible if we base our efforts on industrial symbiosis viability. Industrial symbiosis should strive for sustainability, through circular viability instead of merely efficiency goals.

In Altamira, the outcome of this study shows a low degree of concern for resilience, with firms concentrating all their efforts on their individual efficiency objectives, the lack of resilience hinders sustainability in industrial symbiosis. Additional studies may shed light on the unanswered questions of this paper, especially the static aspect of the study, because it only gathers data from 2016 in Altamira IS, a dynamic approach with historical data in Altamira and in other industrial symbioses may help to achieve a better understanding of the social innovation needed. We recognize that it is usually impossible to capture all the details of an IS, which results in incomplete data, lacking firm/waste/relation/quantity information, thus a sensitivity analysis to assess the impact of missing data is strongly recommended, without ignoring that the reliability of results depends on the quality and completeness of data collected.

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This article is the second in a series of publications aiming to contribute to the understanding of industrial symbiosis as a strategy in the pursuit of strong sustainability in the industrial ecosystem. It derives from a Ph.D. dissertation, proposing a methodology to understand industrial symbiosis. Two case studies are proposed: Dunkirk (France) and Tampico (Mexico). We thank the AISTAC and the environment and security director/manager of each company in the Altamira' IS project for their helpful comments and discussion.

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CHAPTER 7. DUNKIRK INDUSTRIAL SYSTEMIC GOVERNANCE UNDERSTANDING THROUGH A GEOGRAPHICAL PROXIMITY APPROACH

sustainability

MDPI

Article

Industrial Symbiosis Dynamics, a Strategy to Accomplish Complex Analysis: The Dunkirk Case Study

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Abstract: Industrial symbiosis (IS) is presented as an inter-firm organizational strategy with the aim of social innovation that targets material and energy flow optimization but also structural sustainability. In this paper, we present geographical proximity as the theoretical framework used to analyse industrial symbiosis through a methodology based on System Dynamics and the underpinning use of Causal Loop Diagrams, aiming to identify the main drivers and hindrances that reinforce or regulate the industrial symbiosis's sustainability. The understanding of industrial symbiosis is embedded in a theoretical framework that conceptualizes industry as a complex ecosystem in which proximity analysis and stakeholder theory are determinant, giving this methodology a comparative advantage over descriptive statistical forecasting, because it is able to integrate social causal rationality when forecasting attractiveness in a region or individual firm's potential. A successful industrial symbiosis lasts only if it is able to address collective action problems. The stakeholders' influence then becomes essential to the complex understanding of this institution, because by shaping individual behaviour in a social context, industrial symbiosis provides a degree of coordination and cooperation in order to overcome social dilemmas for actors who cannot achieve their own goals alone. The proposed narrative encourages us to draw up scenarios, integrating variables from different motivational value dimensions: efficiency, resilience, cooperation and proximity in the industrial symbiosis. We use the Dunkirk case study to explain the role of geographical systems analysis, identifying loops that reinforce or regulate the sustainability of industrial symbiosis and identifying three leverage points: "Training, workshop and education programs for managers and directors," "Industrial symbiosis governance" and "Agreements in waste regulation conflicts." The social dynamics aims for the consolidation of the network, through stakeholder interaction and explains the local success and failure of every industrial symbiosis through a system dynamics analysis.

Keywords: causal loop diagrams; Dunkirk; industrial symbiosis; complex network analysis; system dynamics

Abstract

Industrial symbiosis (IS) is presented as an inter-firm organizational strategy with the aim of social innovation that targets material and energy flow optimization but also structural sustainability. In this paper, we present geographical proximity as the theoretical framework used to analyse industrial symbiosis through a methodology based on System Dynamics and the underpinning use of Causal Loop Diagrams, aiming to identify the main drivers and hindrances that reinforce or regulate the industrial symbiosis's sustainability. The understanding of industrial symbiosis is embedded in a theoretical framework that conceptualizes industry as a complex ecosystem in which proximity analysis and stakeholder theory are determinant, giving this methodology a comparative advantage over descriptive statistical forecasting, because it is able to integrate social causal rationality when forecasting attractiveness in a region or individual firm's potential. A successful industrial symbiosis lasts only if it is able to address collective action problems. The stakeholders' influence then becomes essential to the complex understanding of this institution, because by shaping individual behaviour in a social context, industrial symbiosis provides a degree of coordination and cooperation in order to overcome social dilemmas for actors who cannot achieve their own goals alone. The proposed narrative encourages us to draw up scenarios, integrating variables from different motivational value dimensions: efficiency, resilience, cooperation and proximity in the industrial symbiosis. We use the Dunkirk case study to explain the role of geographical systems analysis, identifying loops that reinforce or regulate the sustainability of industrial symbiosis and identifying three leverage points: "Training, workshop and education programs for managers and directors," "Industrial symbiosis governance" and "Agreements in waste regulation conflicts." The social dynamics aims for the consolidation of the network, through stakeholder interaction and explains the local success and failure of every industrial symbiosis through a system dynamics analysis.

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INTRODUCTION

In ecology, the concept of symbiosis describes a closed and often long-term interaction between two or more different biological species. This long-term association may, but does not necessarily, benefit both participants. Symbiotic relationships take place naturally in an ecosystem (different communities of living organisms in association with inorganic environmental components). Since 1989, academic literature has shed light on the fact that industry bears a resemblance to natural ecosystems [1], thus closing loops in the industrial socio-ecosystem means the integration of cascading uses, by-product synergies, pooling services and consolidated waste management in an effort of reconciliation with natural ecosystems, even though there are obvious differences from natural ecosystems [2–4]. In recent years, there has been a small but compelling set of studies into the role of Industrial symbiosis stakeholders, such as corporations, SMEs, business associations, anchor tenants and governmental agencies, which has provided enough evidence to recognize the advantages of industrial symbiosis integration in a social ecological dimension [5–9]. Although many studies have focused on industrial symbiosis (IS), most of them focus only on eco-efficiency [10], performance assessments [11] and technical exchange potential using chemical engineering [12]. From the best of our knowledge no significant study has been made into the spatial proximity analysis in the industrial ecosystems. Therefore, the authors accept the challenge to operationalize a systemic approach of social ecological dimension in the industrial symbiosis, through the engagement of applied, social and business management sciences to cope with the spatial proximity analysis of an industrial ecosystem [13,14]. Thus, industrial symbiosis is built towards a common understanding of system dynamics governance in the industrial network, analysed from a broader geographical perspective [15–17].

In this paper, we define industrial symbiosis (IS) as an organizational strategy, which is a sub-field of industrial ecology, considering firms as organized organisms. This metaphor proposes a social innovation where industry entails a semi-closed ecosystem in which material and energy flows should be reincorporated in the system by a circular logic. However, it does not mean that inter-firm actions do not concern individual firms. On the contrary, individual firms must integrate IE in the individual project of their company to allow communication and interdependency as members of the system. Thus, we think of industrial symbiosis as a social innovation strategy, based on the ability to transform global society into one that makes better use of materials. In doing this, we are assuming that social innovations in industry could be triggered by metaphors, which make us think out of the box. In that sense, we are going beyond the definition proposed by Chertow [18], who highlights the technical and biophysical aspects. We are convinced that the human dimension is essential for the understanding of industrial symbiosis as a social process, based on ecological, political, cultural and economic aspects. Although Industrial ecology already claims that the social dimension integration improves the theoretical conceptualization of industrial ecosystems dynamics as evidenced by the French school studies on Territorial industrial ecology [19] then simply Territorial ecology [20]. Indeed, this paper aims to contribute with the discussion about the advantages of using geographical systems dynamic approach to embed complexity in the social analysis of industrial symbiosis, [21], enabling a vision beyond firms' individual actions in the search for eco-efficiency.

1.1. Industrial Symbiosis

Inspired by the previous iconic studies of industrial symbiosis, we identify two main drivers in the analytical process of industrial symbiosis, as mechanisms that steer the sustainable transition of industry. First, the internal firms' production assessment looking for the economic viability window in the intersection between costs reduction coming from efficiency [22] and the valorisation of by-product improving the technical and economic productivity resulting from the cooperative synergies. Where any disruption or reduction in economic benefits may be sufficient to interrupt the symbiotic flow or, in the worst case, force the departure of a firm from the network [8]. The second driver concerns the broader social sphere aiming to understand and develop the stakeholder coordination within the industrial symbiosis. It is within this second mechanism that we can take advantage of a comparative analysis of the geographical proximity issue [16] in industrial symbiosis.

The current debate highlights the circular economy (CE) addressed in our conceptual framework, which proposes to derive strategies for a shift from a linear to a circular industrial structure [14,15,23]. The circular economy is understood in this paper as the extension of value and utility of product, therefore production and consumption wastes are used as secondary resources, providing solutions and co-benefits to a range of economic and environmental issues [4,23]. There are four sources of value creation for the circular economy identified in the literature: 1. The power of the inner circles (the long-lasting durability of products and services), 2. The power of circling longer (the available options of refurbishing, remanufacturing, repairing and reuse of a product or material), 3. The power of cascade use (to diversify reuse along the value chain), 4. The power of pure inputs (biodegradability, uncontaminated materials and the efficiency of collection and redistribution). Looking at industrial symbiosis as an organizational strategy in the quest of social innovation, we take it to be embedded in the Industrial Ecology field, because it is interested in inter-firm relationships, mainly based on cooperation, highlighting the relationship with the biosphere and using ecological ecosystem dynamics as a metaphor. When evoking industrial symbiosis in the paper, we consider it as one of the axes of circular economy, an axe that focus their efforts in the inter-firm relationship strategies, therefore we can assume that industrial symbiosis puts into practice some circular economy principles. However, despite the growing interest in the industrial symbiosis examples the question of how these circular principles work in practice remains unanswered. More discussion about the biophysical and social influence of stakeholders in the industrial ecosystem is required. Which stakeholders? Which motivations? Which values govern the system's structure?

1.2. Dunkirk, Industrial Ecosystem Analysis

The aim of this study, based on results obtained in Dunkirk, is to test the territorial embeddedness of the industrial symbiosis, considered as a social innovative strategy, looking deeper into the systemic proximity understanding of this socio ecological dynamic. To measure geographical proximity, defined as space and relationship distance [24], it seems to be essential to assume that conditions other than the by-product exchange define the geographical location, because by definition, the by-product production firms are multifunctional. Multifunctional firms have functions other than by-product exchange, which usually plays an ancillary role. Therefore, the by-product exchange perspective does not influence *a priori* their location in the territory, establishing a geographical proximity between production and consumption, which is different from monofunctional production [24]. In the multifunctional firms the by-product synergies depend on primary production processes, leading to a direct relationship in which the greater the final production, the more by-products are generated. Thus, a feedback loop is identified in the production side, since the higher the efficiency in reducing waste, the lower the number of by-products available to be shared. The stakeholder relationship network has already been considered in the literature [3,25] but not through a geographical systems dynamic perspective, which would allow us to better understand the mechanisms, motivations and values in the industrial symbiosis for the sake of sustainability, understood in this study simply as the time endurance of this institutional cooperation mechanism.

The Dunkirk case study provides an excellent base for investigation in a developed country, with an existing and available academic literature about the territorial embeddedness of this industrial symbiosis [12,15–17,24,26–29]. Dunkirk encompasses some features that also seem to facilitate the connections between stakeholders and the collaboration in the network, such as the seaport location and the facilitator role played by the local public authority.

The method for evaluating territorial embeddedness in the industrial symbiosis, underlines the key drivers for each stakeholder's behavioural patterns [30], triggering the systems dynamic approach through a Causal Loop Diagram (CLD), with a coherent narrative string to demonstrate if in the Dunkirk industrial symbiosis territories influence and are influenced by, the industrial system. We analyse the interactive behaviour, cooperation, institutional productive capacity, organizational strategies and by-product flow exchanges, which allow us to understand the qualitative nature of such interdependences. Through this study, we provide relevant insights to answer, what are the key drivers that we need to influence to guarantee the essential functions in the industrial symbiosis? The geographical proximity methodology utilized contributes to the complex understanding of social industrial ecosystems, disentangling human motivational causality. In this study, we frame the Dunkirk IS's motivational causality, identified as the economic/political drivers related to the industrial ecosystem structure, the conflicts of interest, game theory, learning process; institutional pathways and idiosyncrasy belong to this social process.

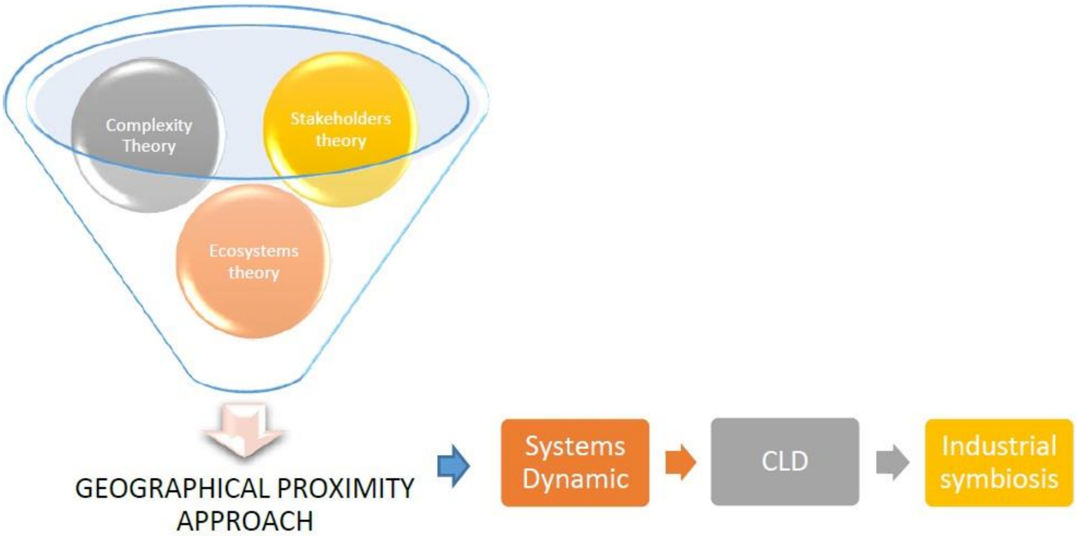

Figure 42. Steps in the geographic system dynamics analysis for industrial symbiosis.

Figure 42, illustrates how the geographical system dynamics approach takes place in the industrial symbiosis, utilizing a common theoretical ground that encompass complexity theory, stakeholders and ecosystems theory, including analytical tools that allow the internalization of complexity in the business and public policies decision-making process. In trying to get a better understanding of the industrial system, an over-simplification of structure would miss some of the properties of the system, because the system's complexity cannot be ignored. In addition, when the ecosystem metaphor is applied to industrial systems, we demonstrate the analytical benefits for the understanding of industrial symbiosis. The industrial ecosystem theory gives room to incorporate complexity into the diversity of industrial stakeholders, supplying them with tools to manage the conflict between different and sometimes contradictory values and interests [24,26,27].

This paper has five sections: In Section 2 we define the theoretical framework for our analysis. Industrial symbiosis is embedded in complexity theory, economic geography theory and ecosystems theory. In Section 3, we introduce system dynamics as a methodology to identify the drivers and leverage points of the industrial symbiosis. The results of the study are analysed using Causal Loop Diagrams (CLD). In Section 4, we discuss the geographical proximity of the Dunkirk industrial symbiosis analysis. Finally, we end the paper with concluding remarks.

THEORETICAL FRAMEWORK

We set the industrial symbiosis understanding on the geographic system dynamics approach for three reasons. First, the approach allows the identification of complex dependence relationships along with the biophysical exchanges accountancy in the industrial network. Based on the recognition of complexity in social industrial ecosystems this paper proposes system dynamics methodology, as a tool to cope with complex adaptive changes [31] in the system, with the ability to produce better long-term scenarios. Second, we argue that geographic economy has explanatory mechanisms for social qualitative analysis, thus industrial symbiosis as the most evolved experience of territorial cooperation between stakeholders, encompasses a profitable arena to get a better understanding of social industrial ecosystems. Last but not least, we use ecosystem theory as a mechanism to approach the system's complexity through the analysis of positive and negative behavioural patterns, a structural analysis that provides a systemic answer to the way actors influence the ecosystem's dynamic.

2.1. Complexity Theory as an Approach to Study the Industrial Symbiosis

Edgar Morin [32,33] has contributed to the construction of the theory of complexity, even if he does not give a definition; he provides food for thoughts regarding the internalization of complexity. Complexity entails a network of concurrent heterogeneous components, which raises the paradox of unity and diversity, encompassing a chain of events, actions, interactions, feedback, decisions and dangers, shaping our biophysical world. Indeed, we need mechanisms to govern complexity in the research for control over entropic phenomena, to reduce uncertainty and to provide certainty to the unforeseen [34]. Complexity seeks to articulate disciplines that were previously disconnected, not because it seeks to gather all knowledge but because complexity implies the recognition of uncertainty, coping with the tension between the aspiration for unified knowledge and the recognition of knowledge gaps.

Complex thinking [34] highlights two characteristics: 1. the whole cannot be reduced to the sum of its parts, 2. the system is an ambiguous concept with blurred boundaries. Complexity introduces the idea of balance/instability dualism, which suggests that there is an imbalance in the flows from the environment and without these flows, an organizational disturbance could trigger the degradation of the system. The idea of an open system, out of equilibrium, moving towards a stabilized dynamism could shed light into the environmental context, engaging complexity in ecosystem theory.

From the beginning of the 21st century, the complex adaptive theory has gained interest in the socio-ecological dimension [3,35], because it has helped to improve the understanding of complex socioeconomic systems, which can be defined as a heterogeneous set of actors that interact with the objective of creating new knowledge, as well as changing the organizational structure. System dynamics appears to be a suitable methodology with the required structure to deal with complexity through the ability to identify causality in processes and track the feedback within the structures. System dynamics is able to identify potential radical changes in complex systems coming as small individual changes, whereas linear or statistical models have a tendency to underestimate or miss this information, because the complex system loses reliability when disaggregated.

2.2. Economic Geography Theory as an Approach to Study Industrial Symbiosis

Economic geography, defined as the coordinated effort to optimize territorial, economic and political resources, is fundamental to the understanding of a functional industrial symbiosis structure; therefore, geographic proximity becomes a relevant variable to steer social ecosystem analysis in industry. The dynamic evolution of the industrial network, evolving in a complex environment, does not allow the firms involved in by-product exchanges to calculate their optimal geographical localization for suppliers and consumers by traditional linear methods. New methodologies need to be tried in the field of geographical economy, analytical tools hanging on complexity in geographic proximity decision making between producers, consumers and institutions. The dynamic geographical approach encompasses two different complementary dimensions of proximity: geographical proximity defined by distance and relationship proximity, an organizational/institutional proximity, which refers to the interwoven network of relationships beyond the physical space [24].

The geographic economy literature has influenced industrial symbiosis analysis [7], offering possibilities for thinking about complexity. Some examples of this contribution are found in the industrial symbiosis academic literature: by-product synergies, waste management and recycling and the geographically oriented stakeholder analyses embedded in socio-material structures.

A relevant critique of geographic economy considers that geographical proximity between actors is not enough to explain the exchanges and the benefit obtained from industrial symbiosis. The theoretical framework of proximity proposes two different visions: organizational proximity and institutional proximity [24]. Organizational proximity "links actors involved, depending on their individual ability to interact and to coordinate activities" whereas institutional proximity "relies on the stakeholders' commitment to a common space of representations, guidelines and rules of collective behaviour." This paper provides an available mechanism to conciliate plurality in the governance of industrial symbiosis [17]. Local governance lays down three main principles to steer industrial symbiosis: 1. Contradictory interests in explaining the dynamics of governance structures, 2. The role of geographic dimension to build up coordination mechanisms, 3. The recognition of contradictory trade-offs values: competition/coordination, global/local, efficiency/resilience, Bottom-up/Top-down, which results in processes of hybridization of institutional representations [36]

We operationalize the geographic proximity framework using the method developed by G. Bridge et al., in References [15,37] who provide a detailed conceptualization of six different socio-geographical dimensions of industrial ecosystems: (i) location, (ii) landscape, (iii) territoriality, (iv) scaling, (v) spatial differentiation and uneven development, (vi) spatial embeddedness and path dependency. These are shown in Table 17. The six geographical dimensions help in the analysis of different territorial strategies, assessing the impact of different variable compositions (location, landscape, territoriality, scale, etc.) in the structures.

Table 17. Geographical proximity grid to operationalize industrial symbiosis (IS).

Dimension	Concept	Example
Location	Refers to the absolute and relative proximity. Due to their transformative character, socio-technical innovations	Fossil energies in transport systems in the 19th century, increased relative proximity between cities with access to railway but on the

	change the location of social and material system entities.	other hand, reduced the relative proximity between cities and rural without access to the railway.
Landscape	Refers how the analyses of socio-technical innovations affect and transform land.	Wind turbines and solar panel constructions; need to emphasize that they bring place-attached emotions and social representations.
Territoriality	Socio-technical systems are spatially determined, encompassing the exertion of power through place-, space- and scale-related governance structures. Three dimensions of territoriality can be identified: contiguity, connectivity and centralization.	Contiguity describes geographical density. that is, transnational energy grids have low contiguity, whereas industrial symbiosis entails high contiguity. Connectivity refers to the points of connection within a system. Centralization refers to the socio-spatial governance distribution degree, that is, a gas pipeline has few connection points (low connectivity), together with few decision points (high centralization).
Scaling	Instrumental variable shedding light on the reconfiguration capacity of socio-technical innovations in terms of who is affected by and who benefits from, a given strategy.	According to their interests, some actors aim to foster local resource cycles through industrial symbiosis, while others might seek to implement (supra-)national recycling systems.
Spatial differentiation and uneven development	Refers to the differences between places, defining how the location and landscape produce intra- and inter-systemic spatial structures and so winners and losers and facilitate or hamper fundamental socio-technical change.	Socio-technical innovations based on common regulations and standards might promote regional convergence, although they might lead to spatial differentiation resulting in uneven regional development.
Spatial embeddedness and path dependency	Refers to capital and institutions such as standards and social practices, not just affecting the systems' exchange potential but also inducing path dependency.	The investment that public authorities make in non-renewable fuels infrastructure determines the paths of future energy investments, locking into some alternatives based on decisions made in the past.

Source: Developed by the authors with insights from [37].

2.3. Ecosystem Theory as an Approach to Study Industrial Symbiosis

Ecosystem theory is showing increasing relevance in the academic community and providing evidence of its benefits [2,4,38], through five main contributions to the scientific literature: 1. it analyses organic networks, presenting not only their positive properties but also the negative ones: trophic competition, depredation, parasitism and destruction of the ecosystem. 2. It recognizes the actors' diversity with their own attributes, motivations and objectives, which determine the rationality of the decisions they make. 3. It frames the rational boundaries of the ecosystem on product/service supply chains, 4. The dynamic evolution of ecosystems is required across time. 5. The identification of behavioural and decisional patterns, which have an influence on the sustainability or decline of the ecosystem itself.

Ecology defines an ecosystem as "a community of living organisms whose vital processes are related to each other and are developed according to the physical factors of their environment." In a broad sense, we use ecosystem as a metaphor in the social sciences referring to system complexity [2]. Since the beginning of the conceptualization of IE as a scientific discipline [1,21,39,40], the concept of a systemic relationship with the biosphere, has established a metaphor with the ecological ecosystem dynamics in which firms are considered as organisms exchanging material and energy between themselves and the environment. In this metaphor, the industry is seen as a semi-closed ecosystem where material and energy flows should be reincorporated in the system by a circular logic. However, it does not mean that inter-firm actions do not concern individual firms. On the contrary, individual firms must integrate IE in the individual project of each company to allow the embeddedness of the members of the system. Some examples of actions to integrate IE in the firm's project are the identification of resource flows (input/output) accountancy, the identification of synergy opportunities and the adoption of the system understanding. We can assume that the industrial ecosystem is not only a concept but also a project of social complexity integration with the aim to achieve sustainability.

Ecosystems can also be conceptualized from a business perspective, highlighting certain tensions present in industrial symbiosis, such as Bottom-up/Top-down, efficiency/resilience, cooperation/competition, global/local, among others [25]. Stakeholders cannot be conceived in a static way, since the network of interactions changes permanently and the purpose of ecosystem conceptualization is to demonstrate the mechanisms of dynamic change [25]. When the ecosystem is handled strategically [4], stakeholders are able to trade off the imbalances with their environment towards a stabilized dynamism, therefore a systematic analysis must be incorporated into the diagnosis, encompassing cause and effect relationships (cost reduction, productivity, efficiency, etc.).

METHODOLOGY

System dynamics is a methodology developed for the study of complex non-linear problems emanating from systems behaviour, able to incorporate, remove or change the structural mechanisms between actors and their idle periods. The publication of books like *Industrial Dynamics* [41], *Urban Dynamics* [42] and *Limits to growth* [43] gave birth to a tradition in the use of system dynamics to study complex issues, incorporating concepts such as retroactive flows and stock variables to the academic research on social systems within an evolutionary framework approach [41]. According to Forrester, J. [42] four features characterize system dynamics when modelling behaviour: 1. a boundary is drawn around the system, 2. retroaction generates ties of structural elements within the boundaries, 3. level variables represent accumulations within the feedback, 4. velocity variables (flow) represent the activity within flows streams.

The Causal Loop Diagram (CLD) developed in this paper for the Dunkirk industrial symbiosis, introduces the concept of feedback loops for key social drivers. A geographical proximity perspective needs to be integrated into the system dynamics approach to cope with behaviour patterns, stakeholder's causal relationships, resources allocation decisions and environmental thresholds which influence future decisions, shaping the social industrial system depicted in the CLD. The system dynamics method addresses complex issues depicting the consequences of stakeholder's behaviours and agreements that may seem counterintuitive in the model. For example, the disruption of one loop like "private resources for innovation" can result in a reinforcing effect (positive polarity) in the "Emerging technology variable" or a balancing effect (negative polarity) in "Eco-efficiency technology" which counteracts or resists the direction of the original flow. The data used in this paper comes from primary and secondary sources. The secondary sources of information include the entire set of scientific papers and reports published in English and French regarding the industrial symbiosis from 1990 to now, gathering different perspectives and addressing different research questions. Besides, as primary sources engaged in this study, we include a set of interviews conducted with expert analysts and researchers that are involved in the organizational process and know in detail the local industry to corroborate the information obtained in the literature.

CLD's are an intermediary step between system conceptualization and the development of a quantitative simulation model. CLD 's may be used as an analytical tool in their own right. In this respect, this study does not extend to a numerical assessment of geographical industrial ecosystems, thereby excluding the model test and simulation of scenarios in qualitative terms; instead, it focuses on problem identification, identification of behavioural patterns and policy design and testing. Once the model is developed and the necessary data gathered, the next rational step in the analysis would be the integration of quantitative assessments to test the validity of the models through simulations.

For the case study, we used data from publicly available sources, interviews, site visits and collaborations with local organizations. Publicly available sources consist of 17 academic papers and reports in English and in French about the Dunkirk industrial symbiosis experience, encompassing different perspectives and addressing different questions. We then cross-validated the publicly available data obtained from the literature analysis presented in the Annex 2 Materials by interviewing some consultants who have repeatedly met with stakeholder of the industrial symbiosis.

The geographical system dynamics approach composed by three previously mentioned theoretical sources: complexity theory, stakeholder theory and ecosystems theory. It is important to provide theoretical foundations for a methodology which, from the best of our knowledge, has never been used in previous research studies, in order to give clarity to the arguments supporting this methodological choice. The geographical system dynamics method tries to integrate the differences while identifying the common features, to ensure their ability to represent territorial mental models, thus one of the main contributions of

CLDs is the identification of key drivers able to cause large-scale changes in the system from small adjustments, a kind of multiplier effect. Even when parallel visions coexist in the understanding of the industrial ecosystem in Dunkirk, the coincidences' identification could contribute to draw up agreements and collective trajectories; therefore, system analysis gives access to structural and long-term simulations of the public policy interventions. The causal variables showed in the CLD offer two categories: 1. The industrial by-product valorisation, and, 2. The pooling of services as innovative strategy in the industrial symbiosis. The previous differentiation follows purposes, seeking to provide clarity to the loops but interlinkages are present in the full diagram depicted in Section 4.1. We designate variable titles by quotation marks in the text. In CLDs, the arrows indicate the causal relationships between the variables. These relationships can have a positive or negative sign. A positive sign implies that variable X connects with variable Y and they move in the same direction (an increase in X leads to an increase in Y and a decrease in X leads to a decrease in Y). A negative relationship implies that the variables move in opposite directions (an increase in X leads to a reduction in Y and a reduction in X leads to an increase in Y. The feedback can both reinforce and balance (marked as R and B in the diagram).

RESULTS

4.1. The Dynamics Governing Industrial Symbiosis at Dunkirk

Dunkirk is located in the north of France. With 88,000 inhabitants in 2016, it is the fifth most populated town in the "*Hauts-de-France*" region. The Dunkirk urban area has grown in a context of rapid territorial industrialization starting in the early 1990s, spurring port activity and the iron and steel industry through bilateral relations between firms which established the core for some early synergies related to waste recycling and energy flows. Since the 1960s, the industrialization of Dunkirk has had environmental consequences, especially atmospheric pollution, which in addition to the economic crisis in the 1990s lead to compelling requests to improve quality of life and environmental regulation. To meet this request, a shared territorial action plan emerged, paving the way for industrial symbiosis implementation, motivated mainly by industrial environment awareness [24].

Increasing conflicts between firms, local residents and environmental protection organizations persuaded local authorities to take part in conflict management and to seek agreements based on the recognition of diverse values regarding the environment [24]. The association of Economy and Ecology Partners in Local Action (ECOPAL in French), was created in 2001 as the local institution in charge of industrial ecology promotion in the territory and encouraging industrial symbiosis in Dunkirk through pooling services assistance. By-product synergies in Dunkirk industrial symbiosis also play a relevant role as depicted in Figure 43, which shows the by-product synergy network in 2018, composed by 14 firms that exchange by-products like scrap, steel slag, refractory bricks, steel mill dust, acid waste, tires, solvents, animal feed and used oil.

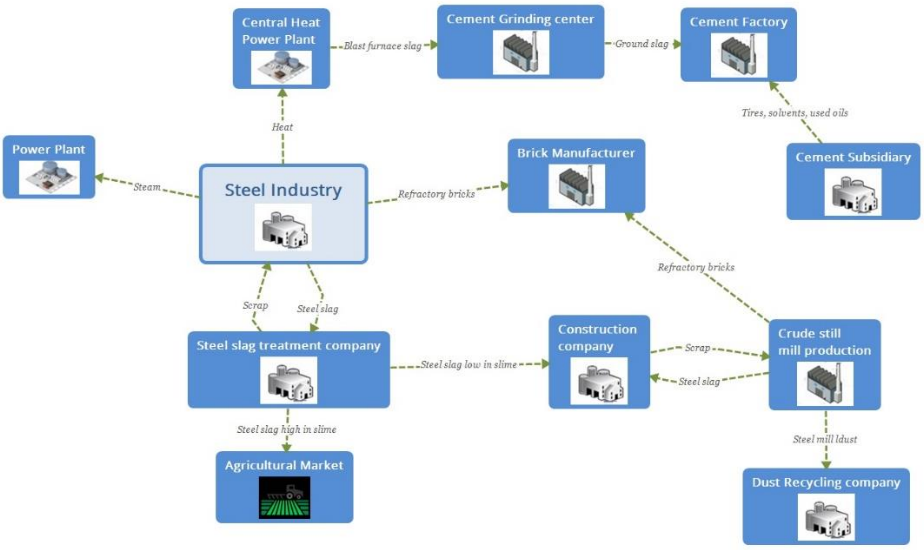

Figure 43. Dunkirk industrial symbiosis network schema.

Source: Modified from [27] and translated to English by authors.

4.2. Drivers for Industrial By-product Valorization in Dunkirk

We have identified "Industrial by-product valorisation" and "Pooling services" as key drivers in the emergence and endurance of industrial symbiosis, thereby influencing territorial embeddedness. The shift from the traditional individual firm logic into a system dynamics analysis implies structural changes in several areas, such as managerial practices, innovation strategies, local policies and the understanding of what used to be economic and political externalities. We start our analysis based on the assumption, derived from the chosen theoretical framework, which establish that the larger the "shift to an industrial symbiosis structure," the higher the "network resilience," encompassing political, economic, cultural and production values. We also identify three reinforcing feedbacks helping the "Industrial by-product valorisation": 1. The less the amount of "Raw materials, energy, transport and landfill expenses," the less "Production costs," reflecting the integration of a by-product integration process through synergetic energy/material exchanges in the industrial ecosystem. Different underlying factors explain this proposed relationship, for instance social cohesion (political support increases when social cohesion increases) and environmental benefits (political support increases with environmental benefits). Savings from industrial by-product valorisation and income from the by-product sales improve the industrial performance in the symbiotic network. 2. Similarly, more "Network resilience" and "Cooperation proximity," spur cooperation within the organizational and institutional structures which has a positive impact on "Trustworthiness." The higher the professional and business confidence in the network, the higher the potential "Collaboration in contracts," thereby supporting the "Industrial by-product valorisation" (reinforcing feedback, R1–R2, Figure 44). 3. The higher the "Industrial by-product valorisation" the higher the "Network resilience," providing diversity in the resource supply and origin, including a local inter-connected exchange network to provide resilience through a diversity of by-product producers and users and accessibility to by-product producers and users in the industrial network (reinforcing feedback R3, Figure 44).

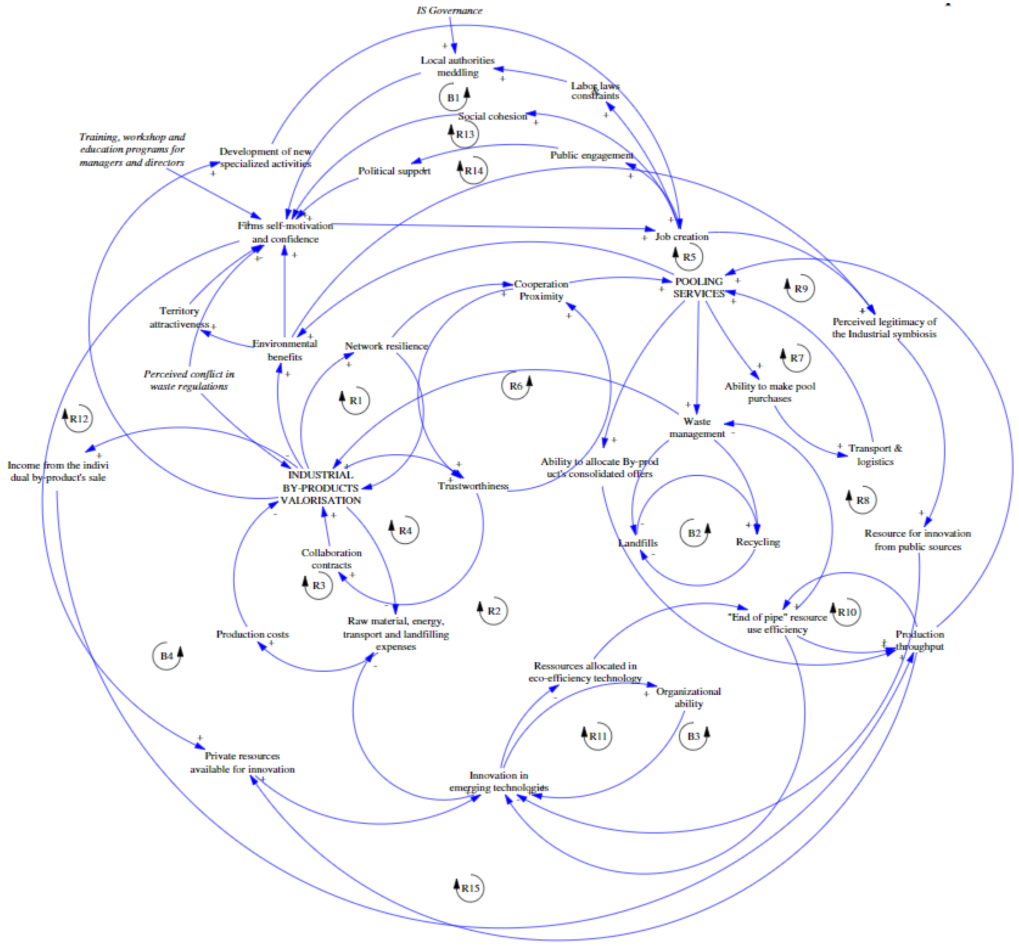

Figure 44. Causal Loop Diagram (CLD) depicting feedback processes in Dunkirk industrial symbiosis. Variables in capital letters represent key drivers in the emergence and endurance of the industrial symbiosis. Variables in italics denote proposed interventions.

4.3. Hindrances to a Systemic Understanding of the Dunkirk Industrial Symbiosis

We have identified two reinforcing feedbacks that counteract the move to industrial by-product valorisation: 1. When "Trustworthiness" is low in the network, the "Cooperation contracts" are also low, which hampers the development of industrial by-product valorisation in the industrial symbiosis (reinforcing feedback, R4, Figure 44), 2. Security of employment conditions and prosperity are fundamental for the territorial legitimacy of the industrial symbiosis. The higher the "Job conditions," the higher "The perceived legitimacy of the industrial symbiosis," obtaining legitimacy from political leaders results in the involvement of local and national authorities in order to supply more "Resources for innovation from public sources," which leads to an increase in the allocation of resources for "Innovation in emerging technologies." The more innovation in emerging technologies for by-product valorisation in the industry, the bigger the reduction in "Production costs," influencing "Industrial by-product valorisation" and in consequence fostering "Development of new specialized activities." The development of new work activities and needs from the network synergies has a positive effect on jobs in the territory (reinforcing feedback, R5, Figure 44).

In addition, there are two lock-in effects created by feedbacks linked to industrial symbiosis' current structure, which have an impact on the likelihood of a change in the industrial by-product valorisation: 1. Currently "Job creation" has a high impact on "Labour and law constraints." The labour regulations influence "Local authorities meddling" which increases the stringency of local and national authorities about the labour regulatory interventions, discouraging "Firms self-motivation and confidence." The less firms are self-motivated and confident in the industrial symbiosis, the less propensity to "Job creation" (balancing feedback, B1, Figure 44). 2. As "Recycling" increases, the waste sent to "Landfills" decreases, so encouraging recycling in the industrial symbiosis weakens the network's capability to transform waste into further by-products for exchange in the symbiosis (balancing feedback, B2, Figure 44). According to the reviewed literature [12,15–17,24,26–29], because symbioses are highly dependent on "Trustworthiness" in the relationship between directors and managers, a misunderstanding between them could mean a rupture in the "Cooperation proximity" influencing the synergy exchange between firms (reinforcing feedback, R6, Figure 44) due to the ancillary status of this by-product activity.

4.4. Drivers of Pooling Services Innovation in the Dunkirk Industrial Symbiosis

We have identified two relevant change processes regarding the Pooling Services potential in the industrial symbiosis: 1. The transport and logistics expenses are a key part of the final production cost, 2. The potential agreements on pooled services in the industrial network spur production throughput. The encouragement of pooling services in the industrial symbiosis depends on the "Ability to make pool purchases," which leads to higher "Transport and logistics" benefits. An additional factor identified as important in this respect is the "Ability to allocate consolidated by-product offers." The more consolidated by-product stocks, the higher the production throughput even if it is outside the industrial symbiosis structure, joining the by-product market rationality (reinforcing feedbacks, R7–R8, Figure 44).

The "Territorial attractiveness" shapes the emergence of industrial symbiosis strategies, which is highly dependent on "Firms self-motivation and confidence." The more confidence and stability in the economic structure, the larger the "Job creation," in turn leading to a higher "Perceived legitimacy of the industrial symbiosis." The more "Resources for innovation from public sources" based on a better social perception of the legitimacy of the industrial symbiosis, the more "Innovation in emerging technologies," which leads to a higher public resource allocation, spurring "Production cost" reduction (reinforcing feedback, R9, Figure 44).

There is a struggle between allocating resources to existing "End of pipe resource use efficiency" technology or investing in "Innovation in emerging technologies." "Innovation in emerging technologies" means a new form of technology which influences the supply chain in a broader way, not just in the internal production of firms (e.g., raw materials, inputs and energy supplies, transport and logistics and landfill expenses). The higher "End of pipe resources use efficiency," the higher "Production throughput" of already existing eco-efficiency technology in the Dunkirk industries (reinforcing feedback, R10, Figure 44). The balancing feedbacks B3 and B4 (Figure 44) represent the fact that resources are limited and that the more resources are allocated either to innovation in emerging technologies or to strengthening current end of pipe eco-efficiency innovation, the less remains to spend elsewhere. The higher "End of pipe resource use efficiency" the lower the available inputs for "Waste management," which in turn means less available inflows for "Industrial by-product valorisation." A decrease in the industrial by-product valorisation entails a decrease in "Income from the individual by-products sale," so a negative influence on "production throughput" occurs. The choice of allocating resources to emerging technologies depends on "Organizational ability," which means the ability of the industrial network and external stakeholders to innovate when facing pressure. The higher "Organizational ability," the bigger the tendency to allocate resources towards new innovation areas. Counteracting such development is a reinforcing feedback which works through the "Raw materials, energy, transport and landfill expenses" (reinforcing feedback, R11, Figure 44).

"Firms self-motivation and confidence" depends on "Social cohesion," as well as "Political support" and "Environmental benefits." Three feedbacks reinforce the increase in "Firms self-motivation and confidence" in the industrial symbiosis at Dunkirk. First, "Income from individual by-product sales" facilitates "Innovation in emerging technologies," which paves the way for cost production optimization beyond the limits of internal productive processes by reducing "Raw material, energy, transport and landfills expenses," which in turn generates a reduction in "Production costs." Cost reduction strengthens the occurrence of "Industrial by-products valorisation" strategies. It also allows "Network resilience" through interactive and learning effects of production processes. Thus, "Cooperation proximity" helps the increase in "Pooling services," further supporting Environmental benefits" (reinforcing feedback, R12, Figure 44).

Another reinforcing feedback is the job creation loop. As "Firms self-motivation and confidence" happens in the industrial system, the stability in the social system boosts economic activity, which in turn creates more job opportunities in the territory, for example through the need to hire specialists in industrial ecology related activities. With higher "Job creation," "Social cohesion" gives attractiveness, encouraging higher "Firms self-motivation and confidence" (reinforcing feedback, R13, Figure 44). We have identified a conflict in waste regulation which is one of the main hindrances in the emergence and sustainability of the industrial symbiosis at Dunkirk. When "Firms self-motivation and confidence" occurs in the industrial symbiosis, it has the potential to increase "Job creation" which in turn generates "Public engagement," facilitating "Political support" and further supporting stakeholder self-motivation and confidence in the cooperation structure (reinforcing feedback, R14, Figure 44).

High "Production costs" in substitution synergies and pooling services are hindering factors in the industrial symbiosis evolution. Lastly, the larger "Industrial by-product valorisation," the higher the "Income from individual by-products sales," driving the industrial ecosystem towards an increase in "Production throughput." The higher the throughput derived from by-product valorisation, the higher the "Private resources available for innovation," leading to "Innovation in emerging technologies," which provides further benefits for the firms by the reduction of "Raw material, energy, transport and landfill expenses."

4.5. Proposed Leverage Points and Interventions

The proposed interventions in the symbiosis (Figure 44—variables in italics) target three different leverage points: "Training, workshop and education programs for managers and directors," "Industrial symbiosis Governance," "Perceived conflicts in waste regulations." The intervention proposed to increase "Firms self-motivation and confidence" is to implement "Training, workshop and education programs for managers and directors." This would increase the ability to undertake industrial symbiosis strategies in the industrial ecosystem, directly strengthening the reinforcing feedbacks R1, R2 and R3 (Figure 44). The "Perceived conflicts in waste regulations" weakens the overall ability to cope with uncertainty in the industrial network and is expected to weaken the reinforcing feedback R5 (Figure 44). Taken together, these developments could support the evolution of industrial symbiosis strategies. An intervention is proposed to increase the "Resources for innovation from public sources" to ensure "Innovation in emerging technologies," thereby creating "Raw material, energy, transport and landfilling expenses" reduction in the industrial symbiosis, as well as a higher potential for the emergence of "Pool services." The proposal to increase levels of "Industrial by-products valorisation" as a value-added step before thinking about "Recycling" aims to improve "Waste management." The proposal to facilitate "Development of new specialized activities" is targeting the fourth driver, "Job creation." By these means, spurring the local industrial ecosystem could gain social legitimacy for industry and address social challenges such as inequality, unemployment and health problems caused by pollution and so contribute to increase "Public support" and political support for the industrial symbiosis strategy.

Political support, in turn, is partly dependent on public perception. "Perceived legitimacy of industrial symbiosis" increases "Public support" but this depends on the ability of the industrial ecosystem to provide environmental benefits (including air and water quality enhancement and reducing the amount of solid wastes send to landfills) and improving labour conditions and providing new job opportunities.

DISCUSSION

The explanatory pathways leading to industrial symbiosis in Dunkirk can be explored through a geographical proximity analysis, using the six geographical dimensions [37] shaped by the CLD analysis. In the Dunkirk industrial ecosystem, proposed interventions rank relatively high according to the literature reviewed and the experts interviewed. Some of the recurrent obstacles that the Dunkirk industrial symbiosis needs to tackle to achieve sustainability include technical, economic, informational, organizational, infrastructural and legislative problems [44,45].

Industrial ecology analyses social relationships, characterized by irreversible and dissipative flows in time and space, this circular understanding of systems is consistent with our understanding of industrial symbiosis, open dynamic systems [42], stakeholder theory [46] and complex adaptive theory [47]. Therefore, industrial symbiosis as a social innovative strategy embedded in Industrial ecology should be able to inspire the sustainability paradigm shift in industry at the local scale [48]. In this study, we frame the socio-economic approach with the theoretical assumption that position dialectic logic at the heart of industrial symbiosis's sustainability [36]: cooperation/competition, efficiency/resilience, local/global and bottom-up/top-down, coming from a coherent theoretical framework. In addition, other relevant insights stress the centralized/de-centralized governance in the symbiosis dynamic: anchor-tenant relationship or scavengers' symbiosis dynamic [7,18].

Location: the territorial scale produces institutions' representations referring to social structures according to our models. At the local level (microsocial), the governance mechanisms are decided and applied by social actors, who at the same time are regulated by those same mechanisms [49]. This analysis shows that lack of communication within stakeholders represents one of the main hindrances to the industrial symbiosis, even when the Absolute geographical location that separates the actors is short. The symbiosis takes place within a perimeter of 17km around the industrial zone, along the coast boarder, starting from the town of *Saint Georges sur l'Aa* to the port of Dunkirk [50], with an average distance of 2–3 km between collaborative firms. From the *Relative location* perspective, the collaboration principle acts on the inter-firm relationships (network members) encouraging them to extend their boundaries thanks to the communication and transport investment in the search for external partner integration (suppliers, customers, municipality, etc.). Industrial symbiosis implementation is determined by several factors, such as the nature of the activities, the history, location, coordination willingness and the existing organizational structure of industrial symbiosis stakeholders [51].

Landscape: The Dunkirk industrial symbiosis is based on electricity, steelmaking slag, heat, scrap, acid waste, refractory brick exchanges and pooling services coordinated by ECOPAL. Electricity production through a residual steam and public heating network have public acceptance, however the increase in steelmaking slag and scrap and increases in wastewater and sewage sludge could face legitimacy problems with regard to the environmental impacts of these activities in the territory. Large-scale infrastructure interventions are likely to cause protests, because of the negative public image of disposal problems. In the industrial symbiosis, the potential scale-up of the public urban heating network might result in landscape changes in the town, due to the industrial strip that surrounds the city, triggering competition with other forms of land use.

Territoriality: The territory of the Dunkirk IS has a decentralized structure (low centralization), as the valorisation of by-product is individually handled by the firms, which produce each by-product independently. The industrial by-product valorisation entails relatively low connectivity and high contiguity, because firms exchange by-products locally. The municipality of Dunkirk is involved in the public heating network and the sewage treatment project, which increases connectivity while decreasing contiguity. Contiguity is high when the raw materials and inputs used in the production process come from the Dunkirk area and low when they are transported over long distances to be integrated into the production process. Industrial symbiosis is an organizational strategy, which fosters contiguity in the geographical dimension of the supply chain. Since the steel and construction industries are essential in the Dunkirk industrial ecosystem, both sectors have a big potential to be strategically embedded in the territory, closing supply and demand loops, supported by emerging technologies and investments as shown in the CLD (balancing feedback B3, Figure

44). The governance structure in Dunkirk encompasses very few stakeholders and is therefore dependent on a small and centralized set of by-products, triggering some structural problems because of the low ubiquity (understood as the number of firms that produce and consume each waste exchanged within the IS) and low diversity of by-products and the small number of firms that produce and consume.

Scaling: Industrial symbiosis is a multi-scale phenomenon—from the microscale of individual firms to the mesoscale of industrial ecosystems. When we talk about industrial ecosystems, we do not ignore the role played by the individual firms, on the contrary we attempt to stress the role of concepts like industrial symbiosis, that provide socially warranted meaning to individual actions, therefore defining how individual firms perceive problems and link them to the potential solutions. Some of the problems that need to be addressed collectively, if firms want to tackle them, are for example water source allocations, by-products synergies, environmental problems, employee qualifications and energy alternatives. At the same time, firms are also involved in global market dynamics, because their final products are usually sold in international markets. Thus, industrial symbiosis should be able to integrate global (large-scale cycles) and local (small-scale cycles), which in the long term is an attempt to balance geographic imbalances by closing global raw materials cycles imported at Dunkirk. This means that the Dunkirk IS seeks to reduce its outside dependence on raw materials and energy through the by-product valorisation and the by-product reincorporation in the industrial ecosystem cycles. From the perspective of the geographical system dynamics approach, we assume that the transitional de-globalization process, usually takes place in the Dunkirk IS case study, without causing shortage related problems (i.e., the transport of low economic value materials is unfeasible due to costs and carbon emissions) but providing an opportunity to supply inflow demand through locally produced by-products. These results cannot be generalized to other industrial symbiosis experiences with different geographical and social environments but it sheds light on an interesting topic that is rarely discussed in the academic Industrial ecology literature.

Spatial differentiation and uneven development: The spatial differentiation of the Dunkirk industrial symbiosis is closely related to location and scaling, since processes of convergence and differentiation find expression in proximities and economies of scale. Spatial differentiation [37] reveals the rework of established patterns, that is, Housing concentration is defined by industrial ecosystems, which provides job opportunities. Regarding uneven development, the current supply sources of the Dunkirk IS are geographically disparate, according to Dunkirk trade balance [52]. With big deficits in carbon oil, waste oil and other raw materials, while at the same time being a global provider of steel, construction, energy, agriculture machinery and inputs for the car and pharmaceutical manufacturing industries.

Spatial embeddedness and path dependency: The current eco-efficiency technology, which has a functional infrastructure to develop "end-of-pipe" solutions, influences and paves the way for the future political and institutional pathways to follow. The highly centralized technological investments and the few opportunities for emerging technologies, hinder the industrial by-product valorisation and the pooling services in the industrial symbiosis strategy. Implementing eco-efficiency strategies based on centralized systems therefore reproduces the lock-ins concerning the socio-ecological industrial ecosystem. Infrastructural decisions for the future induce the path dependencies in Dunkirk, including the political choices of new mono-incineration plants that influence the expected scenarios of the industrial ecosystem for stakeholders and decision-makers.

Table 18. Geographical proximity analysis of the Dunkirk Industrial symbiosis systemic structure.

Geographic Dimension	**Dunkirk Industrial Symbiosis**
Location	Absolute: Short distances in most synergy exchanges Relative: Increase of proximity between the industrial park and the town
Landscape	Potential problems regarding public acceptance
Territoriality	High decentralization of actors during by-product valorisation and consumption High contiguity of by-product consumers and pooling services industries (local industrial ecosystem)
Scaling	Local/regional by-product valorisation and recycling
Spatial differentiation and uneven development	Re-working of local and regional core/periphery patterns
Spatial embeddedness and path dependency	Lock-in of waste regulations and standards.

	Path dependencies due to an existing eco-efficiency expertise and networks between industrial managers and local authorities.

CONCLUSIONS

The conceptualization of governance in IS is not simple to understand and internalize because of the complexity involved in the ecosystem and the stakeholders' conflicts of interest. The success of the IS is mainly related to the governance quest which is the balance between the bottom-up/top-down, cooperation/competition strategies engaged through local/global scales. The governance [53] encompasses ecological, cultural, political and economic embeddedness of actors and the means of governance become crucial to enhance the self-organization. The territorial approach of industrial symbiosis encourage its emergence and sustainability, thus assuring redundancy for key functions. In this study, the functional understanding gains relevance in the Dunkirk industrial symbiosis, when analysing the causal loops through a complex adaptive method for social industrial ecosystems.

Systems analysis is a methodology which aims to improve the understanding of human motivational causality and the network interactions, including the economic and political contextual drivers in the industrial ecosystem, inquiring into stakeholders' behavioural patterns, conflicts of interests, values and motivations. In the literature review, academics define industrial symbiosis as a social innovation which goes beyond the positive scientific approach, we attempt to recognize its standardized dimension, referring to human intentionality and the aim of improving industry. If well steered, industrial symbiosis has the potential to improve innovation and resilience in industry, encouraging industrial ecosystem development, providing a scientific structure to deal with the social intentionality in a systemic way, based on the multiplicity of values, diversity of interests and stakeholder preferences. Looking to make a geographical analysis of industrial symbiosis with a theoretical framework, we draw up six geographical dimensions to improve the systemic understanding able to drive this approach towards a dynamic science [49].

There have been many structurally complex studies of industrial symbiosis at the micro-level but few equivalent studies at the micro- or meso-level looking at the behaviour of actors and its institutions, determined by the social private/public structure.

This study is not exempt from criticisms related to the research method in terms of robustness and validity; the ideas expressed by the experts during the interviews and gathered from the literature review are not directly transferable to industrial symbiosis. The comparability of results with other studies and the generalization of conclusions is debatable; however, the originality of this method can contribute to the understanding of the role of territory in the industrial symbiosis strategy in the search for sustainability. The originality of the geographic system dynamics is based on the richness of references and qualitative information collected, structured in a systemic and reproducible method.

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CONCLUSIONS

This thesis contributes to the industrial ecology and the economic geography literature through the analysis of inter-firms organizational strategies defined as Industrial symbiosis (IS), in the sought of strong sustainability in the industrial ecosystem. We have assessed the Industrial symbiosis causal effects to identify the main hindrances and drivers that regulate or reinforce the sustainability in the complex adaptive system (CAS). It is why we analyze two case studies as a representative sample of industrial symbiosis experiences occurring in developing and developed countries, within different idiosyncratic backgrounds and belonging to different industrial sectors: Altamira (Mexico) and Dunkirk (France). Both empirical studies evaluate the social innovation effects of industrial symbiosis in the dynamics of the industrial ecosystem.

SUMMARY

In academia, the concept of IS has gained purchase in a number of fields including sustainability science, environmental studies and a wide swathe of industrial ecology studies. It is not hard to see its appeal. The concept appears to draw up cooperation as the answer to waste reduction and optimization as well as the resilience integration in the industrial ecosystem. Hence, it is use in both practitioner and academic literatures tends to be approbatory, uncritical descriptive and deeply normative. Given its prominence, it is important that the industrial symbiosis be subjected to critique.

The territory governance analysis presented in this study, where the complex social dimension is integrated through the geographic system dynamics approach helps to overcome routine and path-dependent practices in the IS. Thus, desirable scenarios of IS could be favored over the most likely ones. The territorial approach encourages the IS' emergence and sustainability, assuring redundancy for key functions in the local environment. For example, technical, human and natural resources stock and flows are taking into account at the time of defining the drivers that reinforce the key functions and balance the negative effects that hinder the sustainability of the industrial ecosystem.

Another interesting insight provided in this study is the existence proof of market distortions caused by the operating power relationships within the stakeholders in the industrial ecosystem and beyond. As shown in Figure 44, in Dunkirk, relevant variables other than the market influence, like the territorial attractiveness, political support and the waste regulation legitimacy and stability define the functional structure of the industrial ecosystem, paving the way for transitional pathways where the transactional costs and institutions steer the functional understanding of local industry. Systems analysis improve the understanding of stakeholders' behavioral patterns, unfolding the human motivational causality and the network of interactions.

This thesis focuses on the accomplishment of new **deliberative and strategic dialogue** between local actors (public and private), boosting the recovery of long period matter/energy cycles. This social innovation strategy looks forward for the best integration and improvement of an integrated territory design, fostering transformation of waste valorization into resource through industrial synergies. Whilst IS continues to be idealized in the most reticent spheres as an utopic ideal, where the competition will always impose its strengths over the cooperation, many experiences has shown that resilience and cooperation should integrate the equation of the strong sustainability in industry, encouraging the build-up of politically created markets, material properties and morally defined social relationships.

The first section identifies the theoretical foundation on what we base our assumptions and the development of this study. Regarding industrial symbiosis as an inter-firms strategy that encourages industrial cooperation in a specific geographical ecosystem, we call up the available theoretical frameworks in social and geographical economy fields that let us handle complexity in the social industrial ecosystem in the best possible way. We stand this study over the academic and practitioner ground handing the complex adaptive theory, ecosystems theory, stakeholder's theory as well as the system dynamic theory, that has let us to identify the main drivers and hinders of structural emergence and endurance of industrial symbiosis strategy in the sought of sustainable ways to manage waste and resource scarcity.

The novelty of the geographic system dynamics approach is based on the richness of quantitative data and qualitative references and information collected, structured in a systemic and reproducible method, making possible the comparison of industrial symbiosis experiences, without disregarding the context and environment that define the social motivations, values and resource allocation in the territory. This approach conducted on the symbioses of Dunkirk (France) and Tampico (Mexico) analyses eco-efficiency, collaboration, proximity and resilience assessments and their role in the sought for strong sustainability in the context of every experience. The use of CLD represents an intermediary step between systems conceptualization and the development of quantitative simulation model. CLD 's may however be used as an instrumental and decision making tool in the public policy construction by their own means. In this respect, this study does not attempt to model industrial ecosystems, thereby excluding the model calibration in quantitative terms and test by this time, instead focusing in the problem's identification, identification of behavioral patterns and policy design and testing. Once the model developed and the necessary data gathered the next rational step in the analysis should be the integration of quantitative assessments to test the validity of the models through simulations", like in the project I am steering in the Bezancourt-Pomacle Bio-refinery, which attains the second step of this causal dynamic simulation models. Finally, the CLD method is intuitive and therefore easily spread to stakeholders and policy makers, outstanding the benefits of its adoption in a dynamic industrial model that can deal with the complexity of every experience, incorporating the motivations, values and structure of each territory in the identification, assessment and allocation of the best strategies mix at Circular economy. The methodological framework proposed in this study allows for a continuous and dynamic self-improving approach, integrating feedback when identifying fragilities and improvements to the model, with the aim of making the change management model evaluable and reproducible in other areas of comparable development.

The second section presents some insights gathered from the literature review, like the definition and evolution of strong sustainability postulates, thus justifying its use and implementation as objective to achieve among our assumptions. Holistic and systemic solutions should be proposed effects that feed back to the supply-side of the materials they replace, reduce, or displace. In addition, although different tools can be used to analyze and evaluate the environmental benefits that industrial symbiosis and circular economy can provide to a city. We also unfold a critical review of the existing methodological in terms of robustness and validity; the geographical system dynamic method is not directly transferable to industrial symbiosis. The comparability of results with other studies and the generalization of conclusions are debatable; however, the originality of this method can contribute to the understanding of the social qualitative role in the industrial symbiosis strategy in the search for sustainability. The originality of the geographic system dynamics is based on the richness of references and qualitative information collected, structured in a systemic and reproducible method. This method allows giving answer to several biases like the selection method, regional variability and the non-causality integration, associated with the comparison indexes often used in the literature to evaluate the impact of public policies.

The result of this second section generally shows the positive effect of strong sustainability the Biophysical and the social realm need to be considered through holistic and systemic strategies towards better scenarios in the industry. When we analyze the industrial system through the geographic system dynamic lenses, we are accepting the idea that the allocation of resources is related to the location where the systems are embedded, so the idea of non-substitutability of natural capital, both in the production of consumption goods and as direct provider of utility became inherent to this understanding. We therefore contribute to the definition of what strong sustainability brings about, concluding that complex system as the industrial one, are applied in a territorial dependent context according to the strong sustainability definition, therefore differing from the market logic, where the price is the only determinant of consumption and demand (other drivers considered in the theory as externalities). Thus, stating that the assumed perfect market conditions are almost never present in the reality due to the imperfect use and diffusion of information, effectively taking a detour of the stakeholders' economic behavior.

In the third section, we treat the methodological process where we collect enough evidence to conclude to figure out the work hypothesis of the study, concluding that Circular economy when applied to territories could not be defined by simplistic guidelines like the Waste hierarchy proposed by the WFD, that isolate public decision from the complexity of territorial embeddedness. If we do not critically analyze those kinds of guidelines entailing an oversimplification of the social reality we are going to condemn the circular economy to a pathway dependency on global recycling networks, that currently leads the circularity of materials and energy in a specific geographical configuration. For the OECD countries, Recycling and composting represent 34% of the total MSW in 2013 (OECD Environmental Statistics, 2015), misestimating the other Circular economy alternatives like Industrial Symbiosis, Eco-design, Products lifespan extension, refurbishing, functional economy and responsible consumption as marginal and anecdotic experiences within the Circular economy aims. Uncovering some recycling concerns, like the case studies documented in the UK, where the confluence of politically created markets and the material properties of wastes can unfold the production engagement in a market logic of low-value products, confirming that recycling in global networks could became a wrong way to enact circularity in a given territory.

At the European level the literature review shows that Industrial Ecology (IE) entails three main axes (Gregson, Crang, Fuller, & Holmes, 2015)(ADEME, 2014), where the only significant contribution to waste recovery and resource scarcity in volume is the axe represented by the global recycling networks and energy valorization with a 43.5% (Eurostat, 2019) of the total MSW. Regarding the Goods and services supply and demand axe, where Industrial ecology, functional economy and sustainable supply of resources, we identify the Input Socioeconomic cycling rate (ISCr) = share of secondary materials / processed materials in 9.6% in Europe (EU28) for 2014. (Mayer et al., 2018). Finally, the eco-design in the lifespan extension axe of CE lack of embeddedness, confirmed by a 2008 survey among 36 of China' s larger electrical and electronic manufacturers found little evidence of eco-design in their products (Gregson et al., 2015). However, this result hides the fact that in Europe the global recycling policy tends to be approbatory, uncritical, descriptive and deeply normative, but given its prominence is important to submit recycling to a critical analysis, in light of their aims to reach 50% of MSW diverted from landfills in Europe by 2020. The over-simplistic directives that prioritize ways of managing wastes based on linear assumptions on environmental benefits expectations like the ones postulated by the Waste Hierarchy in the United Kingdom proposed by the WFD, isolating the public policies decisions from the territorial context (Gregson et al., 2015).

In the Altamira "By-products synergy" paper we apply a dynamic analysis locating the territory at the heart of industrial strategies, industrial symbiosis could well replace liberal industrialization policies (global recycling networks) advocated by international institutions (World Bank, IMF, OECD ...) by re-embedding the economy and technology within the biophysical limits of the environment. We also highlight the path dependency influence in the industrial symbiosis process as highly relevant, especially because it is facing multidimensional social processes (interfirm, intrafirm and territorial). This kind of systemic and dynamic analysis provides a better understanding of the feedbacks and driver mechanisms involved in the industrial ecosystem, firm participation/membership, incorporating values and communication skills.

In the final chapter, we analyze industrial symbiosis through a systemic approach, looking forward to integrate resilience in industrial network, widening the efficiency boundaries to the entire supply and distribution chain, including the waste management and by-products and not only to the internal production process, embedded in a territorial structure. The results show in Altamira Industrial symbiosis a negative correlation of -0.495 between efficiency and resilience, which unfold one of the main obstacles to attempt sustainability in the industrial network. Firms invest overall in a high degree of efficiency and centralization in Altamira IS, where only three firms compose the core of the industrial symbiosis (CABOT, INSA and INDELPRO). The interdisciplinary analysis of Altamira IS shows that resetting circular production is possible if efforts are reoriented to strong sustainability, through circular viability instead of merely efficiency goals. The methodology applied to Dunkirk and Altamira industrial symbiosis case study are different, so we are not looking forward to compare the performance of each industrial system, nor even rank them according to shared indicator. We undertake the assumption that each territory is different, encompassing plurality and diversity in the allocation of stock and flow of economic, technological and human resources available, therefore it is possible to analyze their structural dynamic looking forward to optimize its sustainability, but not in the sought of over-simplistic comparisons with other industrial symbiosis experiences.

This highlights the impacts of resilience embeddedness in the industrial symbiosis dynamic, defined in this study as the waste diversity and ubiquity. The diversity represents the number of wastes exchanged between firms and firms' production diversity as the sum of each waste produced by the firm and ubiquity entails here the number of firms that produces and consumes each waste exchanged within the IS. Resilience is strongly linked to the spatial dimension and the geographic systemic dynamic approach unfolded in the Dunkirk case study; it represents a methodology able to integrate complexity in the analysis. Overall this section highlights the governance issue at the industrial symbiosis, which is not simple to understand and internalize because of the complexity involved in the ecosystem and the stakeholders' conflicts of interest. Therefore, we identify an urgent need to integrate complex adaptive systems tracking the institutional changes (Ostrom & Basurto, 2011) approach to better understand the social systems dynamic (Lane, 2008) in industry, that we encompass in the approach called geographical system dynamic.

Finally, the study addresses the issue of structural differences on industrial symbiosis between developing and developed countries. Indeed, the establishment three drivers identified in the Dunkirk case study analysis that could catalyze the sustainability of the industrial symbiosis are different in the form and in the structure from the Altamira case study in Mexico. The governance structure, perceived conflicts in waste regulation and the trainings, education and sensibilization in circular economy for managers and CEO's are different from Mexico to France, encompassing different conditions and features for the proper development of their sustainability. From a methodological perspective, this chapter contributes to the literature by proposing the first time a method to analyze the socioeconomic dimension of industrial symbiosis combines qualitative and quantitative approaches embedded in a geographical systems dynamic method to better understand the social industrial ecosystem. If implemented in Europe the recovery and reintegration of by-products through the production process could exceed the 10% threshold, that has been the maximal rate from 2010 to 2014 (Mayer et al., 2018), thus evidencing the potential of industrial symbiosis as an strategy of circular economy that bet for a territorial embeddedness.

MAIN CHALLENGES

Several struggles have been presented in this work. The positive effects of resilience integration in the assessment of the industrial symbiosis, as well as the systemic analysis of the industry approached with the complexity glasses are not automatic, thus the CLD provides a methodological support to let us know the expected delay for some structural answers and the strategic drivers to catalyze or reinforce the territorial dynamic. The empirical section 4 shows the positive effects of the strong sustainability commitment in the industrial symbiosis, defined as the set of practices and meanings encompassing the dialectic debate about ecosystem's interaction (cooperation/competition), the scale (local/global), the circular viability (efficiency/resilience) and the governance (bottom-up/top-down (Diemer & Morales, 2017).

We conceptualize and propose a definition of industrial symbiosis as an inter-firms organizational strategy in the aim of social innovation, considering firms as organized organisms exchanging material and energy within them and with the environment. This metaphor proposes a social innovation where the industry entails a semi-closed ecosystem where material and energy flows should be reincorporated in the system by a circular logic. However, it does not mean that inter-firms actions do not concern individual firms; on the contrary, individual firms must integrate IE in the individual project of each company to allow communication and interdependency as members of the system. Thus, we think at industrial symbiosis as a disruptive social innovation representing a viable alternative to shift the environmental struggle tendency, holding on the ability to transform global society into a one that conserve and makes better use of materials. In doing this, we are assuming that social innovations in the industry could be triggered by metaphors, which make us think out of the box. We frame the differences in scope between Circular Economy and Industrial Ecology, the former entailing individual firms' dynamic like eco-conception, eco-efficiency and length of use extension, while the former's interest is focus on the inter-firm relationships, mainly based in cooperation, outlining the relationship with the biosphere and drawing up a metaphor with the ecological ecosystems dynamics.

The goal of this geographic systems dynamic methodology, in the hinterlands of systems conceptualization and the development of quantitative simulation model, is to be used as an analytical tool by their own means. In this respect, this study does not extend to a numerical assessment of geographical industrial ecosystems, thereby excluding the model test in quantitative terms and the simulation to test the hypothetic models, instead focusing in the problem and stakeholders' identification, analyzing behavioral patterns and policy design and tests. In Dunkirk for example, we identify "Industrial by-product valorisation" and "Pooling services" as key drivers in the emergence and endurance of industrial symbiosis, thereby influencing territorial embeddedness. The shift from the traditional individual firm logic into a system dynamics analysis implies structural changes in several areas, such as managerial practices, innovation strategies, local policies, and the understanding of what used to be economic and political externalities. The proposed interventions resulting from the causality analysis of the industrial symbiosis target three different leverage points: "Training, workshop and education programs for managers and directors" and "Industrial symbiosis Governance". As we have realized in the study, systems analysis is a methodology, which aims to improve the understanding of human motivational causality and the network interactions, including the economic and political contextual drivers in the industrial ecosystem, inquiring into stakeholders' behavioral patterns, conflicts of interests, values, and motivations.

Over-simplistic directives that prioritize ways of managing wastes on the basis of their supposed or expected environmental benefits like the Waste Hierarchy proposed by the WFD in the UK are isolated from the territorial context and could not represent the social and environmental reality (Gregson et al., 2015). Waste elimination as an end of pipe strategy, as proposed in this prioritizing guidelines is not achievable because the existence of biophysical and economic limits, in the former entropy avoid 100% reintegration of material and energy, regarding the move from available to dispersed systems in biophysical cycles. The latter, avoid 100% eco-efficiency regarding the marginal efficiency of green investments (Olivier, B., 2005). Increase in expenditures match decreasing returns when efficiency attempted higher rates (Less relative efficiency). In addition, scientific evidence has shown that even when relative decoupling between economic growth and environmental impact has been attained in some countries, absolute decoupling is a unattainable objective (Alarcón Ferrari & Chartier, 2018)(Ward et al., 2016)(Faith, Martinico-Perez, Schandl, Fishman, & Tanikawa, 2018) and (Robert-Demontrond & Joyeau, 2010).

This previous analysis let us conclude that uncritical acceptance of global recycling policies as the only significant contribution to CE, attempting to reach 50% of MSW diverted from landfills in Europe by 2020 is risky, the confluence of political created markets of waste and the material properties of those wastes can result in the production of low-value products, lacking of resilience. Therefore, this kind of normative policy lacks of resilience because is not embedded into a territorial context answering for specific industrial and urban needs, but rather following a top-down guideline, which make us conclude that recycling in global networks could became a wrong way to enact circularity in a given territory.

In general, circular economy has positive and negative effects, and the institutional change analysis helps to identify which are the good and bad ways of keeping materials and energy circulating in a specific territory, entailing a potential sustainable mix of strategies. Therefore, concluding that the current challenge is to be critical, when analyzing the available alternatives to enact circularity of materials and energy in a specific territorial configuration, integrating all the available alternatives in a systemic structure able to encompass complexity from the moral economy, path dependency, institutional structure and territorial context to figure out the optimal structure for each system.

LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

This thesis covers case studies from both developed and developing countries. Methodologies adapted to the structure of each territory were used to minimize the potential biases inherent in the evaluation of industrial symbiosis impacts as the strategy spurring industrial cooperation in the territory. However, in order to improve the external validity of the results found in this thesis, it would be interesting to replicate the tools developed here to other cases. The next rational step of this study, once the model developed and the necessary data gathered, is the integration of quantitative assessments to test the validity of the models through simulations. The use of the same methodology in future works would make possible the validation of the simulations delivered. This methodological choice has the advantage of decision-making appropriation and the participatory process of the systems construction, where the stakeholders got involved in the process. Thus, once verified the strengths of the geographical systems dynamic approach the accumulation of knowledge and the self-emergence of more collaborative projects in the industrial ecosystem will be uncovered, with the support of public incentives pushing forward, the right strategic drivers with the ability of reinforce the collaborative potential and the sustainability of the territory.

Even when the methodology and theoretical framework applied in this study offers an analytical tool by their own means, supporting the systems conceptualization and the development of quantitative simulation model. In this respect, this study do not extend to a numerical assessment of geographical industrial ecosystems, thereby excluding the model testing and the simulation, instead focusing in the problem identification, proposing behavioral patterns modifications and policy recommendations. Once the model developed in the next stage with the necessary data gathered, we could attempt the integration of quantitative assessments to test the validity of the models through simulations". Indeed, the integration of quantitative data throughout the use utilization of more technical methodologies like econometrics could be a relevant option to demonstrate the correlation between resilience and efficiency, for example.

This study is not exempt from criticisms related to the research method in terms of robustness and validity; the ideas expressed by the experts during the interviews and gathered from the literature review are not directly transferable to IS. The comparability of results with other studies and the generalization of conclusions are debatable; however, the originality of this methodology can contribute to the understanding of the role of territory in the industrial symbiosis strategy in the search for strong sustainability. The originality of the geographic system dynamics is based on the richness of references and qualitative information collected, structured in a systemic and reproducible method.

The author through the Industrial Bio-economy Chair of NEOMA- Business School, institution where I am based as early career researcher, and the Jean Monnet Excellence Center for Sustainability (ERASME) has already engaged three different projects in France with different levels of progress concerning Dunkirk, Reims and Montélimar. The Dunkirk municipality in collaboration with the AGUR, the EIT Club and Dunkerque Promotions directors has already showed their interest in the pursuit of the second stage of the study presented in the Chapter 7. The second stage of this study looks forward to include the quantitative data of the identified drivers, to forecast scenarios and recommend public policy interventions in the pursuit of the strong territorial sustainability. To achieve this objective the necessary means will unfolded from a research investment budget coming from the ADEME and Dunkerque Promotions.

The second project supported by the Grand Reims and Reims Metropole in collaboration with the Biotechnology and Bio-economy European Center (CEBB by its acronym in French) looks for the consolidation of IS in the Pomacle-Bezancourt bio-refinery (Santos & Magrini, 2018) as an institution (Roggero et al., 2018) that has the potential to contribute to the industrial ecosystems sustainability. In this starting project, we introduce IS as a social innovation in the field of ecosystem cooperation looking forward to coupling the bio-refinery concept and the IS approach, invigorating traditional agro-industrial regions. Utilizing for this purpose the geographic systems dynamic methodology to analyze IS using Causal Loop Diagrams to identify the main drivers and hinders that reinforce or regulate the industrial symbiosis' sustainability. We use the Bezancourt-Pomacle Bio-refinery case study to explain the role of geographical analysis in a region with strong tradition in agriculture and agro-industry. Four scenarios seek be portrayed (reference, short, mid and long terms) with the support of a synergy matrix and material flow analysis, integrating variables from different motivational values dimensions: efficiency, resilience, cooperation, and proximity in the IS. This study can prompt current recycling regulation towards multi-sectorial arrangements, which can contribute to regional resilience, because it is able to integrate the social causal rationality when forecasting attractiveness in a region or individual firms' potential.

Finally, in Montelimar, the author is collaborating with the early stage development of the Bio-economy guidelines, where the Geographic System Dynamics methodology fits as the stewardship strategy looking for the articulation of transversal activities and economic sectors, where the territorial approach can contribute to improve the local sustainability and the creation of the value on the territory.

Beyond the France boarders, others studies are emerging on the effects of social causal drivers in developing countries, they are still very scant and often anecdotic. The scarcity of these studies is largely due to the lack of data gathering skills from the public authority and the confidentiality issues and the secrecy of sensitive information. Notwithstanding, the implementation, monitoring and evaluation of the geographical system dynamic methodology is subject to a self-improving process due to the continuum feedback incorporation into the systemic causal structure, becoming more precise over the time and incorporating the dynamic changes that every social structure experiments in the long term. It would be interesting to carry out more in depth analysis, in not only the industrial symbiosis structure but also adapted to urban metabolism, sustainable cities and agricultural and food systems like the Bio-refineries. This would be the subject of future work in order to formulate recommendations of public policies according to each industrial ecosystem structure.

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ANNEX 1.

ENTRETIEN SUR LA TRANSITION SOUTENABLE D'UNE SYMBIOSE INDUSTRIELLE

Site: ZIP Dunkerque.

Interviewer: Manuel MORALES RUBIO

Date: 09/Juillet/2018

Ce projet s'intègre dans un travail de recherche doctorale, qui entend identifier les forces et les faiblesses, les contraintes et les opportunités (économiques, sociales, environnementales) dans la mise en place d'une symbiose industrielle. Cette enquête doit nous aider à mieux comprendre les interactions présentes au sein des symbioses industrielles dans le cadre d'une stratégie de développement durable (forte) et au regard d'une approche ancrée dans la dynamique des systèmes.

Cette analyse systémique et dynamique permet de mieux comprendre les mécanismes de rétroaction (effets feedback) présents dans l'écosystème industriel, la participation et l'adhésion de l'entreprise, l'intégration de valeurs et de compétences en matière de communication.

Nous comprenons qu'il est souvent difficile de donner des réponses concrètes à ce type de questionnaire, toutefois l'objectif est bien de cerner vos perceptions des symbioses industrielles. Les résultats du travail sont bien entendu confidentiels, un rapport vous sera adressé ultérieurement.

Nous vous remercions encore pour le temps consacré à cet entretien. Le questionnaire compte 12 questions et il est conçu pour durer une quarantaine de minutes.

COORDONNÉES GENERAUX

Enterprise ______________________________ Poste ______________________________________

Ancienneté dans l'organisation (même si promotion de poste) __________________

Localisation géographique du poste________________

ECOLOGIE

1. Matières et énergie

Quel est l'origine (géographique, vierge) de la matière première et de l'énergie (renouvelable) employées dans le processus de production de l'éco système industrielle?

Donnez une note d'évaluation de satisfaction pour le critère énoncé ci-dessus (5 est la meilleure note)

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

2. L'eau et l'air

Quelle est la qualité de l'eau et de l'air sur votre territoire et comment l'écosystème industrielle contribue à sa conservation ou à son amélioration ?

Donne une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

3. Mobilité

La distribution des produits finaux et la mobilité des salariés pour se déplacer sur leur lieu de travail sont-elles prises en compte ? Connaissiez-vous des stratégies visant à améliorer la mobilité des personnes et des marchandises ?

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

ECONOMIE

1. Avantages et difficultés

Quels sont les bénéfices et les difficultés économiques rencontrés suite à la mise en place de la symbiose?

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

2. Coopération

Considérez-vous que la symbiose industrielle repose principalement sur une coopération entre les différents acteurs? Comment cette coopération fonctionne-t-elle dans la pratique? Connaissiez-vous des exemples ?

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5

Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

3. Acteur publique

Quel est (ou a été) le rôle de l'état (et des collectivités locales) dans la mise en place de la symbiose sur le territoire?

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

GOUVERNANCE

1. Organisation et pouvoir publique

Quel a été votre rôle dans la symbiose ? Avez-vous participé directement à sa mise en place ? Considérez-vous que la symbiose a été créée sur la base d'un leadership (une personne qui a porté le projet du début jusqu'à la fin) ? Si c'est le cas est-ce que ce leadership a créé une réelle dynamique porteuse ?

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

2. Règlementation et légalité

Est-ce que le territoire a mise en place un système de suivi concernant le bon respect des règles internes, droits des salariées, d'égalité et de justice ? Lesquelles ? Est-ce que les parties prenantes participent aux a la recherche de synergie ? Lesquelles ?

____

____

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

3. Communication

Est-ce que la liberté d'expression et d'accès à l'information permet aux salaries d'exprimer leur insatisfaction face à toute mesure imposée ?

____

____

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

Comment la communication (formelle ou informelle) a-t-elle influencé la mise en place des synergies ?

____

____

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5

Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

CULTURE

1. Créativité et loisir

Est-ce que le territoire soutient la participation des activités créatives et innovantes ? Est-ce que ces activités contribuent directement aux différents projets de la symbiose industrielle ?

___

___

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

2. Recherche et enseignement

Comment la symbiose influence-t-elle les activités de recherche et de développement de votre entreprise ? Favorise-t-elle également la promotion des programmes de formation répondant aux besoins de l'écosystème industriel ? Est-ce que les interactions formelles et informelles entre les ressources humaines à l'intérieur du réseau (symbiose) encouragent l'innovation et l'émergence de nouvelles idées?

___

___

Donnez une note d'évaluation pour le critère énoncé ci-dessus (5 c'est la meilleure note).

1	2	3	4	5
Critical	Mauvaise	Satisfaisant	Bonne	Vibrant

SYMBIOSE INDUSTRIELLE

Recueil de données pour traitement et analyse quantitative. L'étude porte sur l'émergence et le fonctionnement des symbioses industrielles ainsi que leur évolution historique. Il s'agit de mieux comprendre les mécanismes de transition d'une gestion des déchets vers une co-construction d'un marché des sous-produits. L'étude entend également analyser la façon dans laquelle les coproduits sont transformées en marchandise, ne possèdent pas auparavant de valeur d'usage et de valeur économique, mais dont le volume est lié à la production principale.

- Liste de sous-produits et déchets produits à Dunkerque et sa gestion (destination), valorisations.

- Volume (tons, m^3, kw, etc.) des productions des sous-produit par année depuis 1995

- Echanges de chaleur fatale ou gaz résiduel, échanges physiques (non monétaires) ou réductions de coûts contractualisées avec les entreprises partenaires.

-économies générées par les synergies et poids (en %).

-Emplois crées sur la ZIP de Dunkerque directement en relation avec la filière de traitement des déchets, soit en fonction de réglementations environnementales imposées, ou pour la valorisation des sous-produits en synergie avec des autres organisations, depuis 1995.

ANNEX 2

METHODOLOGICAL STEPS FOR THE SYSTEMATIC LITERATURE REVIEW OF PAPER IN CHAPTER 7

We selected the content analysis methodology, which is based on three phases: pre-analysis, data exploitation (categorization and coding), and the processing of the outcome. After transcription, we proceeded to a vertical analysis of each interview to identify key themes, after that the horizontal analysis between interviews took place, to identify recurring themes. For coding, we chose a manual processing mode. Finally, for the treatment of the results, we relied on a grid of interpretation permitting classification and categorization of the raw data resulting from the interviews.

Our review process uses the journal-ranking website Scimago Lab. In Scimago Lab., we chose "environmental sciences", "aquatic sciences" and "business and international management" as the subject categories. We set the region country option to include "all". The span of the period investigated is from 2000 to 2018. Following that, we listed the journals classified as quartile 1 (Q1), which are in the top 25% of academic journals in their subject categories. In the "environmental sciences" category there are 339 journals, with 68 defined as Q1. In the "aquatic sciences" category there are 217 journals, with 53 journals defined as Q1. In the "business and international management" category, there are 386 journals, with 90 defined as Q1. Comparing these, three lists and after deleting duplicates, we obtained a final list of five journals.

In these five journals, we searched using the words "industrial ecology" and "Dunkirk" using the ScienceDirect™ Core Collection of Thomson Reuters. We placed each word in the topic field and the name of the journal in the publication field. The topic field and the name of the journal were connected by "and". Topic fields includes the title, summary, keywords by author, and Keywords Plus®. Keyword Plus® are the original keywords provided by Thomson Reuters. The period of the search was from 2007 to 2018.

We obtained a list of 10 papers as a result. We checked the abstracts of the 10 papers and isolated the papers that do not address the complexity of the Dunkirk industrial ecosystem, discarding four papers that were dealt with specific technical ecological or environmental degradation issues.

Considering that this is a French case study, we wanted to include the relevant French literature not translated into English, so we did a similar bibliometric research in the Documentary website of the National Center of Scientific Research in France (CNRS in French), in the "Man and society" category. We searched using the words "écologie industrielle" and "Dunkerque" in the topic field. The topic field as in the ScienceDirect™ version includes the title, summary, keywords by author and Keywords Plus®. The period of the search was from 2007 to 2018. We obtained a list of 16 papers as a result. We checked the abstracts of the 16 papers and isolated those that do not address the industrial ecosystem issue in Dunkirk, discarding nine papers.

To the final list of six papers in English and five papers in French, we add one more paper in English and two in French located in the "Economics and Econometrics" category, published in low ranking journals, and three official reports published by local authorities' or research firms engaged to this aim by local authorities in the region, that the authors consider relevant to the main objective of the paper - contributing to the understanding of the industrial ecosystem dynamic in Dunkirk. Consequently, we obtained a final list of 17 papers and reports for review in total, both in English and in French (see Full list available in Annex 1).

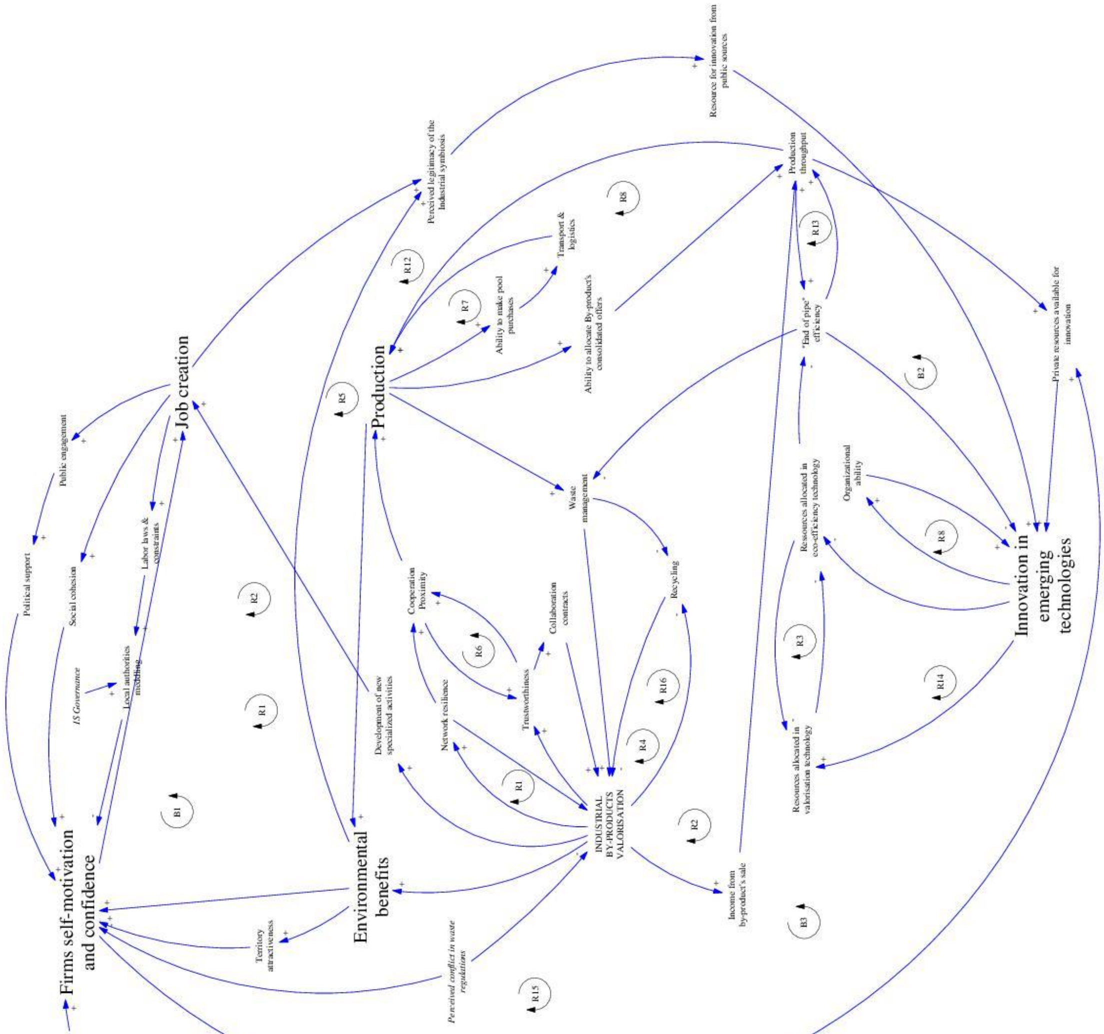
The papers used the concept of life-cycle assessment, sustainability assessment and stakeholder management, historical evolutionary management, and social network analysis. However, two intentions were implemented in this procedure. First, in the field of environmental science, the phrase industrial ecology is used in various formulations such as Industrial symbiosis, green economy, sociotechnical transitions, circular economy, territorial ecosystem, and eco-innovative park. Because of this diversity, we tried to collect the appropriate papers by using "industrial ecology" as a search keyword. Second, we collected samples from Q1 journals; these publications hold leading positions in academia and represent the major discussion of the ecosystem concept.

This process can be classified as a systematic review. A systematic review usually includes a meta-analysis, which requires that the researches include the statistical estimation. However, a major part of the reviewed papers adopted qualitative research methods, as explained in the following sections. Consequently, we decided to proceed to the systematic review without the meta-analysis.

Table 19. The number of papers by journal

Title of the Journal	**Range of the publication year**	**Number of papers**
Cleaner Production	2016-2018	5
Ecological Economics	2017	1
Research in Transportation Business & Management	2017	1
Développement durable et territoires	2014	1
Revue d'économie industrielle	2015	1
Revue ISTE Openscience	2018	1
Journal of Canadian regional studies	2017	1
Dunkirk Report - EURAENERGIE	2018	1
OREE	2013	1
Innovation research network	2015	1
Revue Géographie, Economie et Société	2012	1
Revue d'Economie Régionale & urbaine	2011	1
Flux	2017	1

ANNEX 3


Firms self-motivation and confidence
Job creation
Production
Environmental benefits
Innovation in emerging technologies
INDUSTRIAL BY-PRODUCTS VALORISATION
Perceived legitimacy of the Industrial symbiosis
Resource for innovation from public sources
Production throughput
Private resources available for innovation
Transport & logistics
Ability to make pool purchases
Ability to allocate By-product's consolidated offers
"End of pipe" efficiency
Public engagement
Political support
Social cohesion
Labor laws & constraints
IS Governance
Local authorities mobbing
Waste management
Recycling
Organizational ability
Resources allocated in eco-efficiency technology
Resources allocated in valorisation technology
Cooperation Proximity
Collaboration contracts
Trustworthiness
Network resilience
Development of new specialized activities
Territory attractiveness
Perceived conflict in waste regulations
Income from by-product's sale
Training, workshop and education programs for managers and directors