



HAL
open science

Economic analysis of eco-industrial parks : a transactional approach for synergies valuation and risk management

Robin Molinier

► **To cite this version:**

Robin Molinier. Economic analysis of eco-industrial parks : a transactional approach for synergies valuation and risk management. Other. Université Paris Saclay (COmUE), 2018. English. NNT : 2018SACLCO97 . tel-02020848

HAL Id: tel-02020848

<https://theses.hal.science/tel-02020848v1>

Submitted on 15 Feb 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Economic analysis of eco-industrial parks: a transactional approach for synergies valuation and risk management

Thèse de doctorat de l'Université Paris-Saclay
préparée à CentraleSupélec

École doctorale n°573 Approches interdisciplinaires, fondements,
applications et innovation (Interfaces)
Spécialité de doctorat : Sciences et technologies industrielles

Thèse présentée et soutenue à Paris-Saclay, le 28/11/2018, par

Robin Molinier

Composition du Jury :

André Torre Directeur de recherche, INRA/ AgroParisTech Université Paris-Saclay (UMR SAD-APT INRA/AgroParisTech, équipe Proximités)	Président
Catherine Azzaro-Pantel Professeur des universités, Université de Toulouse (INP ENSIACET, Laboratoire de génie chimique)	Rapporteuse
Hubert Stahn Professeur des universités, Université Aix-Marseille (Faculté d'économie et de gestion, Groupement de recherche en économie quantitative)	Rapporteur
Daniel Llerena Professeur des universités, Université Grenoble Alpes (Laboratoire d'économie appliquée)	Examineur
Jean-Guy Devezeaux de Lavergne Ingénieur chercheur, Docteur d'État, directeur de recherche CEA (Institut de technico-économie des systèmes énergétiques)	Examineur
Nathalie Mionetto Déléguée Territoriale, Docteur, FCBA (Institut Technologie Forêt Cellulose Bois construction ameublement)	Examineur
Elisabeth LeNet Ingénieur chercheur, Docteur, CEA (Institut de technico-économie des systèmes énergétiques)	Encadrante
Pascal Da Costa Maître de conférences HDR, CentraleSupélec Université Paris-Saclay (Laboratoire de Génie Industriel)	Directeur de thèse

*"To get the full value of a joy you must
have somebody to divide it with"*

Mark Twain

Acknowledgements:

My gratitude goes to my top-gun supervisors Elisabeth LeNet, Pascal Da Costa, Jean-Claude Bocquet and Jean-Guy Devezeaux de Lavergne for their rigor, patient guidance and useful advices on my research work. I am also grateful to Catherine Azzaro-Pantel, Hubert Stahn, André Torre and Daniel Llerena for their comments and their participation to the Ph.D. committee.

In general, all the people I met in CEA and CentraleSupélec, including my colleagues from I-tésé and LGI, have always been very kind and brilliant people. To my dear colleagues and friends, the PhD students there, Antoine, Camille, Linh, Maryeme, Olfa and Martin, as well as Miika and Kati, thank you all!

Special thanks to Patricia Thibaud for her energy and magical effectiveness as an assistant.

I want to thanks the many people who helped me one way or another. It includes the experts and practitionners with who i learned a lot and progressed as a scientist and industrial ecology expert. Despite their busy schedule, their answers to my questions and the long discussions we had allowed me to gain precious insights ill always keep in mind. I am particularly glad to acknowledge the support provided by NorskeSkog Golbey, and notably Jean-Francois Serre, Timothé Houillon and Maxime Laurent as well as Airliquide with Fabrice Del Corso and Moulay Driss Elalaouifaris who followed up my work and gave me opportunities and ideas to deepen my knowledge of the real world industry and more generally to enhance my work.

Titre:

Analyse économique des éco-parcs industriels: une approche par les transactions pour la valorisation des synergies et la gestion des risques

Résumé: Les travaux présentés dans ce mémoire étudient les problématiques transactionnelles posées par le développement des éco-parcs industriels (EPI). Nos travaux visent donc à fournir une analyse économique des synergies éco-industrielles (substitution de ressource, mutualisation d'infrastructures) afin de compléter les approches techniques principalement développées en sciences de l'ingénieur. Notre unité d'analyse sera donc les transactions matérialisant les relations entre acteurs au sein des symbioses industrielles (SI) notamment les modalités contractuelles et les choix de capacités. Premièrement, nous étudierons les pratiques de mise en synergie ayant cours au sein des EPI en fonctionnement au travers d'une revue de la littérature; en résulte une proposition de typologie des pratiques de synergies éco-industrielles ainsi qu'une représentation de leur processus de mise en oeuvre.

Pour compléter cet état des lieux, nous décrivons et analysons le cas de l'EPI Green Valley (France). Nous caractérisons et mettons en perspective son développement et les principaux facteurs ayant affecté son processus de déploiement. Ensuite, en faisant appel à des arguments issus de l'économie des coûts de transaction, nous proposons l'usage de contrats de long terme complexes pour organiser les transactions associées aux SI. En conséquence, un cadre de conception des contrats incluant des clauses spécifiques (tarification, pénalités, garanties) est proposé de manière à tarifier les flux et à partager le risque. Dans une dernière partie, nous étudions les décisions d'investissement en capacités mutualisées via la modélisation économique, et ce dans un contexte coopératif et un contexte non-coopératif. Les paramètres

clés (taille, coûts de "back-up", facteur d'échelle) et les variables de décision (investissement, engagement) sont analysés. Les incertitudes sur les besoins collectifs futurs sont traitées selon deux approches: Laplace et min-max regret. Dans chaque cas, le choix de capacité optimale est décrit en fonction des paramètres.

Mots clés: Economie des coûts de transaction, éco-parcs industriels, synergies industrielles.

Title:

Economic analysis of eco-industrial parks: a transactional approach for synergies valuation and risk management

Abstract: This thesis report aims at addressing transactional issues raised by the undertaking of eco-industrial parks (EIP) development. The economics of eco-industrial synergies (resource "flow" substitution and infrastructure/service "capacity" sharing) is investigated so as to complement existing engineering-oriented approaches. A focus is made on industrial stakeholders' interplay in industrial symbiosis (IS) and their strategic decision-making in terms of investment and contracting practices. First, a survey of practices actually observed in EIPs in function is conducted through a literature review. A taxonomy of eco-industrial synergies is thus proposed and an IS implementation process representation is derived.

Then we conduct a case study on the Green Valley eco-industrial park (France) to characterize its development and gain in depth knowledge on driving factors involved in IS deployment process.

Then, from economic arguments (transaction costs) we advocate the use of long term contracting in organizing IS related transactions. Following this, a contract design framework including specific provisions (tarification, penalties, warranties) is proposed in order to perform pricing of flows exchanges and risk sharing. In a last part, investment decisions in shared capacities is studied using economic modelling both in cooperative and non-cooperative game setting. Key economic parameters (size, back-up costs, scaling factor) and behavioral decisions (investment, commitment) are described and uncertainty is treated in two different approaches: Laplace formulation and robust decision making. In each case, optimal investment in capacities is derived.

Keywords: Transaction cost economics, eco-industrial parks, industrial synergies.

Contents

0	Introduction: Industrial ecology and the circular economy	15
1	From a state of the art to the object of study: what are industrial symbioses and eco-industrial parks ?	29
1.1	Techno-economic vision of industrial symbioses: material and energy flows, costs and engineering issues	30
1.1.1	Synergies through resources substitution	30
1.1.2	Synergies through infrastructure/service sharing	37
1.1.3	Industrial symbioses in practice: towards a taxonomy	44
1.1.4	Modelling tools applied to industrial symbioses	48
1.2	Socio-economic vision of industrial symbioses: Eco-industrial parks, roles and networking	59
1.2.1	The process of industrial symbioses implementation: economic roles towards transactions	68
1.2.2	Modelling and analyzing eco-industrial parks	76
1.2.3	Eco-industrial parks developments: experiments, challenges and driving factors	82
1.3	Synthesis and recommendations	84
2	Perspectives on Industrial Symbioses: Case study-the Green	

Valley eco-industrial park	87
2.1 Case study description	87
2.2 General approach and research questions	89
2.3 Analysis	91
2.3.1 Territorial context	91
2.3.2 Sectoral context	91
2.3.3 Actors at stake: resources and objectives	92
2.4 Results and discussions	96
2.4.1 Sequence of events (chronological development)	96
2.4.2 Social ties	106
2.4.3 Organisational structures	107
2.4.4 Regulatory and policy aspects	109
2.5 Synthesis and recommendations for eco-industrial parks analysis	111
3 Economic modelling of resource substitution synergies	115
3.1 Transactions, organization and economic governance: a literature review	115
3.1.1 Contracts in economic governance	115
3.1.2 Contracting process models: partnering and negotiation	121
3.2 Contract design framework for industrial symbioses	133
3.2.1 The use of contracts: Uncertainties and asset specificity in industrial symbioses	133
3.2.2 Contracts architecture: lessons from the literature	140
3.2.3 Substitution synergies as a multi-period buyer-seller relationship	158
3.2.4 Analysis-contractual design guidelines	169
3.3 Synthesis and recommendations	177

4	Economic modelling of Infrastructure sharing synergies	181
4.1	Economics of infrastructure sharing synergies: basics derived from the literature	181
4.2	Economic models of infrastructure sharing	187
4.2.1	General model: elements and notations	187
4.2.2	Capacity oversizing under uncertainty-Laplace criterion	193
4.2.3	Capacity oversizing under uncertainty-MinMaxRegret criterion	202
4.2.4	Capacity oversizing under uncertainty: non-cooperative formulation	208
4.3	Synthesis and recommandations	212
5	Conclusion: results and perspectives for eco-industrial parks development	215
	Bibliography	233
	A list of EIPs	258

Chapter 0

Introduction: Industrial ecology and the circular economy

In every discipline ranging from physics to economics the various phenomena can be represented and captured within a formal framework using flowcharts and schemes to extract the core insights of the system under study. This idea of a scheme is well adapted to industrial sciences whose the aim is to provide a complete set of concepts and approaches for scientists and engineers to understand and then enhance the value creating systems. Such an idea stands behind the notion of circular economy (Geissdoerfer et al., 2017). The circularity patterns of these techno-economic systems have to be understood as opposed to the linearity that characterises most of actual industrial systems representations and their related analytical frameworks. The concept of the circular economy can only be fruitful if it is viewed as an innovative and disruptive framework tailored to describe, assess and design more sustainable industrial systems. The circular economy as a field must then be understood then as an approach and as a set of objects. The systemic perspective it conveys applies to human led processes having effect on natu-

ral resources consumption and energy uses as well as pollutants production. Indeed, by being defined in opposition to what can be denoted as the "linear economy" which is based on a systemic point of view in which the key operators can be summarized as Take-Make-Dispose, the circular economy deals with techno-economic systems considered and designed so as to achieve resources conservation (for an extensive discussion, see Kirchherr et al., 2017). Circular economy, by closing the loop, has many implications in terms of real world situations but it also raises many scientific challenges because of the nature of the objects to be studied and the lack of researches done so far about these systems and this framework. The originating work carried out in such a direction were prospective studies by club de Rome experts "the limits of growth ?" (Meadows, Meadows, Randers, and Behrens III, 1972) which raised the issues related to the scenario of increasing scarcity of natural resources (excessive pollution, land use issues, mineral and fossil resources depletion) due to the large development of industrialization and huge consumption needs due to the increase of world population size.

Basic complete scientific studies about circular schemes for activities were introduced in the work about the "Cradle-to-Cradle" approach (McDonough and Braungart, 2010). The key idea standing behind the concept of circularity in an economic context is to relate goals of achieving economic value creation with the decrease of material and natural resources depletion in order to face the stakes associated to their scarcity. A circular economy aims at improving value creation (that could be accounted for with the GDP indicator) without accelerating the depletion of natural resources through raw material extraction through different reverse recovery chains from product reuse (the most efficient) to the recycling of materials (the longest in terms of conversions steps, thus the less efficient). It then comes that the added

value associated to industrial activities must be de-coupled from resource consumption by setting up innovative integrated business models aiming at adopting tailored design practices, operational strategies and consumer management to fit with these objectives of perpetual value recovery along the newly defined product life-cycle so that key circularity concepts must be reviewed. The circular economy raises many issues to assess the potential gains to be earned as well as the challenges it supposes (relative efficiency of reverse recovery chains and quality concerns). Moreover different scales must be adopted when one analyses this concept (McCarthy et al., 2018). As it is a framework for economic systems the scales can vary from the isolated industrial process of a given focal firm or a supply chain for a given good to the economy at a more or less extended geographic area.

A particular business structure that could take advantage of proximities to benefit from the advantages of circular activities is the Eco-Industrial Parks (EIP). In these structures the circular economy is implemented in localized and integrated industrial areas within which companies use shared assets and common equipments generating "infrastructure/service sharing synergies" and exchange flows of materials or energy that would have been wasted otherwise, that is the generation of "resource substitution synergies"¹ (Lowe, 1997). This kind of structure is already existing in France with the eco-industrial parks of Le Havre, Pomacle, Dunkerque and Green Valley² but the first system of this type was born in Kalundborg (Denmark). Many initiatives of this type exists across the world (Boons et al., 2017) and public authorities are interested in EIPs deployment in many regions (Oree, 2016). In this kind of structures the circularity is achieved thank to the principles of

¹see Chapter 1 for an extensive discussion.

²see Chapter 2 for a detailed analysis of this case study.

Industrial Ecology (I.E) which considers industrial areas as a symbiotic ecological system which is restorative by design as the activities involved within such an area recover value from fatal heat or disposed outputs that are used as inputs by the eco park members, thus achieving resources conservation while ensuring economic development.

Allenby et al. (1994) proposed a new analytical perspective on industrial activities based on ecological systems evolutions. Using the seminal proposition of Frosch and Gallopoulos (1992) they conceptualized 3 types of industrial ecosystems functioning using industrial ecology as a "[...] unique systems approach within which environmental issues can be comprehensively addressed. It is based on an analogy of industrial systems to natural ecological systems". Following their perspective industrial ecosystems are characterized by 3 evolution stages. For the ecosystem of "Type 1" incoming resources are illimited and the waste generated by the activities can be illimited because carrying capacity of the environment is sufficiently available to dispose them off.

The "Type 2" ecosystem is characterized by limited resources and bounded carrying capacities for waste disposal so that the members within the ecosystem are more interdependant (rivalry, complementarities) and more exchanges occur within the ecosystem which is then more efficient than in the former type. The last stage in the evolution ("Type 3") consists in an ecosystem in which waste and resources cannot be distinguished since exchanges are cycling within the ecosystem. Renewable energy being the only incoming resource to the system. Industrial ecology should then help to reach the third stage of evolution in order to achieve sustainability. Such a perspective relates to the environmental Kuznets curve from Grossman and Krueger (1995) whose investigations towards the link between pollution and economic devel-

opment exhibit an inverted U shape showing that growth at some point can be negatively correlated with pollution. Industrial systems can be increasingly efficient due to people preferences towards better standard of living, technological change and economic dematerialization.

Lowe and Evans (1995) defines "Industrial ecology (IE) as " an emerging framework for environmental management, seeking transformation of the industrial system in order to match its inputs and outputs to planetary and local carrying capacity." while Ayres et al. (1996) insists on its paradigmatic shift from technology-based solutions to environmental concerns "Industrial Ecology is perhaps the first serious attempt to go beyond general statements regarding the desirability of 'clean technology' and to assess realistically and quantitatively the range of practicable possibilities for reducing materials extraction, consumption and waste."

This vision is at the root of the ecological economics stream of research.

In a more "operational" view, Ehrenfeld (2004) proposes to define I.E as a conceptual tool striving for designing more sustainable economic systems: "Industrial ecology is a new system for describing and designing sustainable economies. Arising out of an ecological metaphor, it offers guidelines to designers of products and the institutional structures in which production and consumption occur, as well as frameworks for the analysis of complex material and energy flows across economies." The linkages with natural or biological "Ecology" is reaffirmed in his definition. This conceptual familiarity leads to conceptual debates about the nature of I.E. This question is notably adressed in John Ehrenfeld's 2004 contribution explicitly titled as "Industrial ecology: a new field or only a metaphor?" (Ehrenfeld, 2004). Limits on the parallel between natural and socio-economic systems are discussed and it is argued that such a representation can be used as an innovation tool.

Institutionalisation is a step to be still completed for I.E to become a field in itself with its community of researchers, academic journals and conferences, education standards (for example in business schools) and business practitioners. Nowadays this step seems to be almost completed since journals, conferences, academic curricula and I.E inspired initiatives do exist in several countries all around the world (France, Korea, Switzerland, the USA ...). This conceptual debate not cleared yet³but it expresses the richness of the idea carried out by this research object.

Industrial ecology thus tends to change the way industrial eco-systems do function through the realisation of Industrial Symbiosis (IS). I.E has some overlapp with circular economy paradigm but assumes a wider range of synergetic strategies and multiple flows interconnexions across organizations, sectors and geographic areas as stated by Chertow (2000): "Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products.". At the difference of some circular economy inspired models that are rather oriented towards a perspective focusing on a focal flow supply chain (Closed loop supply chain). This distinctive feature is adresses in Bansal and McKnight (2009) who emphasises the key differences between the supply chain perspective and industrial ecology.

Specificities of EIP and IS are numerous. The degree of cooperation, information exchange requirements and interdependant operations strategy of transactors is indeed high as well as asset specificity (even site specific), dependency of demands and supplies on the core process activity (implying

³We participated in 2017 to the Young Researchers Colloquia on Industrial Ecology in Troyes (France) in which the debate between the tenants of I.E as a "field of study" and the ones considering it as a "methodological corpus" was salient.

some risks), quality concerns (rising equipment or operational costs and limits exchange possibilities) and lack of tailored expertise (resulting in under-efficiency or the need for third party collaboration through contracts or Joint Ventures).

IS are then the modalities by which I.E manifests in real systems in function. IS deployment thus intricates several steps from concept to project and from project to effective transactions.

Research questions adressed in this thesis

Industrial ecology appears as a potential powerful conceptual tool to design techno-economic systems enabled to tackle the concerns related to natural resource depletion, localization of employment and energetic autonomy. Nevertheless its promising potential must be discussed and rigourously adressed by economists, engineers and researachers in other fields in order to identify the achievable outcomes and the traps to be avoided for this framework to play effectively its role in real situations for global economic and environmental improvement. The consideration of individual actors and their interactions within transactions have received so far little attention in the literature on industrial ecology, eco-industrial parks and industrial symbiosis. Some authors nevertheless pointed out that such aspect cannot be neglected when it comes about understanding the concrete and effective deployment of symbioses. Andrews (2000) insisted on the need for micro-foundations for industrial ecology using social sciences and economics due to its object of study: "My summary point is that industrial ecology is to a large extent about organizational issues, especially transactions within and among firms". The author insists on this aspect when proposing a research agenda for I.E: "Most important, we need to direct additional effort to behavioral topics".

This caveat about misconceptions of what makes I.E distinctive from natural "ecology" has not been followed by tailored work on the question of economic transactions supporting IS but rather by contributions from the sociology (see Chapter 1.2). In recent contributions this point has been raised again: "The role of actors' power over resources is therefore an important area for future research [...]. While contractual agreements may be one way to control for such dependencies [...], they also raise transaction costs, which may inhibit new exchanges. Understanding under what conditions power asymmetry may support or inhibit IS and how this can be managed may offer practical insight into strategic actors exiting an IS system." in Walls and Paquin (2015) or in the engineering contribution of Kuznetsova and Zio (2015) " Almost all decision-making approaches account for the global optimization objectives, without considering the local IA (individual actors) preferences for their interconnections [...] However, these local objectives are mainly related to the technical feasibility objectives and not to the objectives of each IA as an individual intelligent player of EIP. In this view, the EIP design process requires more robust 'balancing' of distributed intelligence and desires of IA with global objectives for EIP design."

Those contributions highlight that the deployment of IS requires to conceptualize the phenomenon as a process involving many actors over several dimensions to convert I.E based initiatives into effective transactions over resource exchanges and asset uses. Economics has looked at any of these microeconomic issues in "standard" business contexts dealing with classical (linear) supply chains but not in IS.

This need for economics on cooperation in EIP and IS business models led us to undertake this work in the context of a Phd dissertation.

Our central research question is the following,

"How to handle IS specificities (value and risks) so as to favour the commitment of actors to a suitable and sustainable transaction ?"

In this report, we thus propose a structuration of eco-industrial synergies implementation in EIPs as a process towards multilateral commitment to a transaction and study in detail the economics of such transactions.

Thesis outline and results summary

The content of our investigations is organized the following way.

In the first chapter (Chapter 1) we draw on a state of the art of the literature about Industrial Symbiosis and Eco-Industrial Parks and derive many results about the complex object of study of this work that is the transaction setting process leading to the realization of industrial symbioses. In the first section (Section 1.1), the focal objects of analysis that are the "resource substitution synergies" (1.1.1) and the "infrastructure sharing synergies" (1.1.2) are characterized economically by the description of their respective cost structures and value drivers (business model). In a subsequent subsection (1.1.3), a taxonomy of real world IS practices is proposed on the basis of the study of a selected sample of EIPs in the world (whose detailed description is available in the Appendix-A). The taxonomy we propose allows to identify the nature and function of flows (respectively assets and equipments) exchanged (resp. shared) in EIPs for resource substitution synergies (resp. infrastructure sharing synergies). It is a useful information to be used to target the elements likely to be involved in IS in real world initiatives. In a last subsection we present the research contributions about the development of modelling tools for industrial symbiosis launching process. We first review the "diagnosis"

tools whose aim is to identify potential valuable exchanges opportunities leveraging information on a particular geographical area. We emphasise that such tools are used in upstream phases of the IS implementation process. A review of "performance indexes" proposed in the literature is then performed in order to made accessible evaluation tools for the practitioners and researchers. Last but not least, we present the set of contributions dealing with the "design and optimisation" of flows exchanges. We complete the work done recently by Boix et al. (2015) on this topic by describing the latest contributions and we point out the advantages and limits of such approaches when it comes about inter-organisational relationships. Social dimensions are of first importance in the study of IS implementation process since it pertains to its nature. As a consequence, in the second section of this first chapter we study the literature about the relationships and roles of actors who implement (or try to implement) such synergies in the eco-industrial parks. Here we characterize the role of actors, the organisational structures and the various factors having influence on the behavior of those actors towards the realisation of IS, notably the policy and regulatory aspects. In the next part (1.2-a) we propose a new definition of an EIP by differentiating this form from other form of networked businesses on the basis of a literature review. Then the organisational structuration of the existing EIPs is described using a framework developed in the literature (Boons et al., 2017). The various economic roles that actors can play in an EIP are then detailed along a proposition, inspired from the literature, with a focus on economic functions performed and insisting on the importance of individual behavior. We then propose a process representation of IS implementation from I.E inspired initiatives to transaction setting and exchanges realisation (1.2.1). Once such representation is framed, we review literature on I.S and EIPs

from the fields of sociology and complex systems modelling. We delineate the key social dimensions and influencing relationships and their structure in EIPs and we draw on a state of the art of modelling techniques applied to EIP analysis (Agent-Based Modelling and Social network analysis) and considering the interactions of multiple agents insisting on the scarcity of industrial organization and game theoretical models endogenizing transactions. In the two last subsections (1.2.3 and 1.2.4) practical developments of EIPs are reviewed and challenges are raised. We review and classify the factors driving the issue of IS implementation process in EIPs on the basis of existing references and own identified factors. Such a reflection allows to characterize the key factors influencing IS deployment, notably the regulatory and policy related ones that provide insightful information to public and institutional actors interested in the development of I.E.

Chapter 2 consists in the case study of the Green Valley EIP. Considering the scarcity of well documented examples of EIP in function all around the world (24) and the fine grained information required to gain insights on transactional processes (contracts, plant strategy, applicable regulations...) we conducted this case study on an EIP in France, the "Green Valley" EIP. This EIP is therefore an additional one. The interest of this case study is three fold. First it makes available an additional (detailed) case of EIP to the research and practitioners community. Second, it proposes a new instance to test theoretical predictions and empirical patterns observed in the former case studies and we show that this case is quite emblematic on some dimensions and original on others. Third the interest of this case study is that due to the in-depth information we raised about actors strategy and contracting. It has given a unique "learning field" to complement our reflex-

ions with insights directly drawn from practitioners' experience and vision. After a presentation of our objectives and methodology we go into the details about the EIP (context, actors) and then propose a detailed description of phenomenas and events (then the dynamics) characterizing this EIP. We finally put this case in perspective with a set of key patterns identified in the literature and we give indications on how does this case fits or complement literature insights.

Economic modelling per se is the object of the two subsequent chapters in which we investigate the strategic decisions of actors when committing to each synergies archetypes. Chapters 3 and 4, each focusing more specifically on "resource substitution synergies" and "infrastructure sharing synergies" from the point of view of actors directly implicated in such practices.

The first section of chapter 3 (3.1) proposes a state of the art on economic governance of transactions insisting on the role of long term contracting as one mechanism for transactions organization. The various theoretical tools from game theory and microeconomics are also reviewed in (3.1.2) making the link between classical problems (coalitions, negotiation, information) and their salience in industrial ecology. In the second section (3.2) we propose a contract design framework for resource substitution synergies. First, specific characteristics of transactions over resource substitution are studied so as to determine the transaction governance options that is long term contracting. Then in order to frame the applicable contract forms and provisions, we introduce elements from the literature in management research and supply chain management and we propose a generic contract structure. In the two last subsections of this chapter, we propose a modelling framework for resource substitution synergies contract setting. In 3.2.3, we begin by a definition of

the economic problem structure raised by resource substitution insisting on the various decisions that actors should take (over different time horizons) the key technical and economic parameters of the transaction and the risks associated to them. From this problem definition and the elements at stake for the actors, we come up with a contract design proposition integrating specific provisions tailored to handle the risks embedded in resource substitution synergies so as to favour actors commitment to the transaction, that is to ease the effective implementation of industrial symbioses.

In chapter 4 we specifically focus on infrastructure/service sharing synergies. In a first section we recall the economic foundations of such a practice insisting on the fact that the key driving parameter is a capacity choice. Elements from the literature are presented to establish the cost and value drivers of sharing and the possible organisations that can be encountered in reality. Following this, we propose an economics based modelling of infrastructure/service sharing synergies as a capacity choice problem under uncertainty. The subsequent subsections consist in the resolution of this problem for two radically different decision under uncertainty approaches (Laplace and minmaxregret). Theoretical results are first derived so as to investigate solution properties.

Optimisation and simulations are then performed using the 3 key parameters we introduced in our modelling and give insights on how all those 3 parameters drives the final capacity choices and the economic outcomes. Results are completed with the use of additional parameters (bargaining power, substitution resource cost advantage, time value of money) to gain additional economic insights. In the last section (4.2.4) of the chapter we formulate the problem as a non-cooperative game between 2 different capacity builders so as to understand the possible outcomes (3 equilibria occurs) issued from

gaming on infrastructure building and sharing.

We conclude our work in chapter 5 where we state the insights, recommendations and further research propositions we derived along our investigations.

Chapter 1

From a state of the art to the object of study: what are industrial symbioses and eco-industrial parks ?

The eco-industrial reasoning applied to a territory sheds light on what resources could be recovered from waste streams and what assets could achieve higher rates of utilization according to sharing opportunities.

Overall efficiency can be improved for participating firms individually and for the global economic system.

The eco-industrial park exhibits a set of potential synergies to be implemented through synergistic business collaborations among its associated actors. In practice the economic synergies are induced by two types of (possibly interacting) strategies: Resource substitution/recovery and infrastructure/service sharing.

In a first section we characterize economically the two types of synergies and

the issues raised to their implementation. Then we propose a taxonomy of those two archetypes following a literature review on eco-industrial parks. A literature review on the modelling techniques developed in the literature to identify, evaluate and design synergies is conducted. In the second section we propose a definition of eco-industrial parks and point out key differences with other kind of networked businesses. We review the taxonomy of EIP development dynamics and follow by proposing a process representation of industrial symbioses implementation in EIPs. Modelling techniques and their application to the analysis of EIPs are reviewed in a last part of the chapter.

1.1 Techno-economic vision of industrial symbioses: material and energy flows, costs and engineering issues

1.1.1 Synergies through resources substitution

The first set of strategies to improve the eco-system efficiency consists in replacing the use of virgin resources by *substitution resources* recovered from the diversion of waste disposal streams of another actor activities (including fatal heat). Following such a strategy environmental benefits are achieved. On one hand, diversion of waste streams discharge reduces the environmental footprint of production activities and on the other hand, the use of virgin raw materials from the natural capital is limited thanks to the alternative use of waste as input. Nevertheless it is argued that this kind of practices may maintain some polluting industries efficient and then do not contribute to an overall environmental harm reduction compared to cleaner technologies use. Moreover such strategies do not incentivize producers to limit their

waste generation since it is valuable and then potentially conflicting with the adoption of cleaner processes or technologies. The last argument the point is rather to analyse what is the priorities for polluters as the value recovery strategy must be complementary with direct waste reduction strategies. Economically the relevance of using waste inputs in place of newly produced ones is to benefit from purchasing cost reductions compared to its usual input source. Indeed the substitution solution is also dependent upon which costs are avoided and incurred by the waste generator in order to be able to trade his waste. Thus this strategy is intrinsically two-sided as a (set of) source generator(s) flows have to match the requirements of a (set of) sink(s). Transaction triggers are thus associated with a set of requirements on both technical and economic dimensions.

Specificities of IS flows

On the technical side quantity and quality patterns of the exchanged flow must satisfy a set of receiver specifications to be appropriately used. First the available quantity of a given by-product can be too low for being considered in the mix of inputs. Moreover there is no ex-ante guarantee that the waste or by-product targeted for symbiotic exchange meets a minimal quality standard for further use by the client since by definition such by-product is not designed for this purpose. Pollutents or impurities in the by-product composition can lower the quality of clients production and cause damages to the receivers' equipments. Interconnections of process water can suffer from the same kind of burdens. Final product quality decrease can harm market position of the reciever and cause higher maintenance costs or equipment replacement. Regularity of both the quantity and the quality is another source of availability risk associated to the exchange of wastes and/or by-products.

Higher volatility in the quality and/or the quantity can make the planning process less efficient and impose the recourse to an other source of back-up inputs or higher inventory levels to cope with irregularities. In order to cope with those issues, adjustments can be performed in order to make the waste flow matching the specifications at least partially. The costs of such adjustment operations must be accounted in the total cost of recovery. When matching requirements is assumed such operations must therefore be considered as value-adding ones. Different configurations are possible when dealing with waste value recovery. Upgrading tasks can be performed by the seller, the buyer and a third-party service provider (waste treatment and recycling specialists).

Recovery operations can be performed at each stage in suitable specific equipments or installations that will process the targeted waste stream before transmission to the next recovery echelon (either transfer to the final user or to an intermediate waste processing compagny specialist to perform further tasks for full recovery). Additional use of energy, materials or chemicals may be needed to achieve recovery. The positioning of a third-party in between the source and the sink can be explained by several interacting factors such as legal constraints, specific capabilities or efficiency gains. For heat recovery and transfer some specialist capabilities are needed and the transfer system is maintained and operated by a third party actor and not by source (sink) company staff. For the by-product to be transfered from the emitting source to the demanding sink, the product average quality and satisfactory regularity have to be achieved using more or less extensive and intensive treatments along the recovery/transfer chain. The transfer options differ with the by-product to be exchanged. Piping systems are used for fluid transmission as process water, heat transfers (hot water or steam) and industrial gases.

Classical logistics schemes including transportation by trucks and warehousing are suited to solid waste (or by-products) as ashes, cinders, gypsum, wood residuals-organic waste, residential waste. Different cost structures are then applicable.

Piping system cost consists in the purchased equipment, its installation and maintenance. The two main drivers for piping costs are the length and the flow rate (diameter). Logistics cost components are trucks, workforce, fuels and insurances. Logistics can be performed internally or outsourced to a third-party logistics service provider. Logistics service cost drivers are the travel distance, product complexity or specificities (requiring costly sorting and conditioning operations) and even specific containers.

Valuing substitution resource use

The decision of using recovered by-products as inputs can be performed after appropriate costing and tariff setting. This economic evaluation of the symbiosis opportunity should demonstrate mutual benefits for the involved actors. Cost savings is a first motivation for using substitution since for the supplier it can reduce treatment and disposal costs. and for the buyer it can achieve savings regarding input purchases by introducing by-products from the source in his mix.

Synergetic exchange thus arise under the condition that the total costs to be incurred in order to recover and use the substitution material or energy is lower than the purchasing cost of a usual alternative input or utility. The total cost of production for the by-product (regarding a particular final use) has to account for both required investments in tailored installations and operational expenses. The cost of investments is variable depending on which

asset is required. Fixed-capital investment accounts for all the expenses required to set productive asset.

Fixed-capital investment components can be splitted in manufacturing or non-manufacturing parts. The manufacturing part is directly related to the requirements imposed on asset's productive operations.

Depending on the asset under consideration and the objective of the investment, the focus can be made on subsets of cost components from the complete breakdowns proposed in classic industrial or chemical engineering handbooks (Chauvel et al., 2001; Couper et al., 2008).

The main cost driver for fixed-capital investments is the installation (or plant) capacity. If the construction of an entire plant is necessary, a high amount of capital will be required and collective *project finance* arrangements must be designed unless traditional equity or debt financing is applicable. Such a configuration can be observed with large industrial incinerators CHP-energy plants construction or district heating networks. If the synergy consists in a less capital intensive effort (pipeline connection to a existing network or plant) the problem of capital recovery still remains. The source of capital used to invest will affect assets financing cost. Debt loans and equity funding can be mixed to reach the required amount of money for investing. Those sources exhibit different properties. *Equity financing* is firm specific in the sense that it implies liability of the whole firms assets and is the most exposed to default risks. Accordingly the cost of capital associated to equity financing must be evaluated regarding requirements for raising equity from investors by using the average (or expected) *return on capital* for similar projects in case of full equity financing. In case of mixed sources the *capital asset pricing model* (CAPM) prices equity using the sum of the *risk-free* asset return (usually public bonds) with the market risk premium (evaluated by the dif-

ference between the return of a stock market index with the risk-free rate) multiplied by firms stocks β . The β coefficient accounts for the sensitivity of firm stocks to market fluctuations.

In case of *debt financing* the interest rate depends on risks incurred by the lender so that the debt cost drivers are technology maturity and uncertainties associated to eco-industrial development as noted by Lowe (1997). Generally debt is assumed risk-free and its cost is the interest rate. If *default* is a possible issue the cost of debt must be increased by *default risk premiums* and *return premiums* (Cooper and Davydenko, 2001). Moreover depending on the mix of debt *layers* (seniorities) risk implies several different interest rates. Financial cost is then accounted for as a *weighted averaged cost of capital* (WACC). At this point we must be careful when evaluating such a cost for a given (eco-industrial) project. Indeed the equity cost is related to the firm value patterns and not for the specific project under evaluation unless it exhibits the same patterns than the other firms projects. The latter might not be true for eco-industrial projects thus adjustments must be performed on the traditional cost of equity computation through modifications of the β coefficient. Considering a portfolio of comparable firms acting in the project's sector rather than a global market index can be suitable. Procedures to perform such modifications must take into account differences in capital structures of the targeted comparable alternatives. Moreover the capital structure of the project can vary over time (depending on debt layers and term structures) and thus the discount rate must change over projects lifespan. Debt financing allow to achieve tax savings as long as the taxable income is lowered due to financial expenses (tax shield). Capital recovery must be achieved for the symbiosis to be economically sustainable. The generation of free cash flows are then dependent upon *operational expenses* which ac-

count for the costs incurred during the operating time of the industrial asset. Those expenses can be variable costs and thus depend upon the activity level measured as the quantity produced, transferred (throughput), treated or used depending on the tasks required by the symbiosis.

Operational expenses are also characterized by a fixed part which is not sensitive to variations in activity levels. Workers daily operating the asset and maintenance costs belong in this category. The variable costs to be incurred in performing waste or by-product recovery is energy (electric power for pumping systems) or intermediate product consumption (chemicals for treatments).

Revenues from by-product or waste sales will contribute to cash flow generation for the source actor whereas for the sink the use of a substitution resource will not generate revenue but rather cost savings. At this point we must recall that the source actor can also benefit from "pure" cost reductions from the transaction if the by-product production cost is lower than its alternative treatment cost (if applicable). For the source actor, transaction is profitable if the treatment cost savings and the by-product sales allow to recover the cost of investments. For the sink actor operating cost savings are achieved if the total reductions in purchasing costs (due to substitution) outweigh the total pre-processing costs associated with the substitution resource use. Sink actor will benefit from the transaction if those net savings will in turn outweigh the investment costs incurred for participating in the transaction. Investment cost recovery (and thus profitability) is then driven by the total value of trade and the costs to be incurred to run the necessary recovery, transfer and pre-treatment operations. Transaction outcomes are highly influenced by the economic context in terms of values (alternative price, treatment costs, intermediate chemical prices ...) as well as in terms

of trade volume due to fluctuations on the participants core activities affecting by-product supply and demand. Negotiations of tariffs and contractual arrangements can shape transaction expected outcomes in order to favour investment cost recovery for each participating actor. Economic criteria for symbioses outcomes evaluation can adopt several perspectives regarding basic assumptions on uncertainty, dynamics and the relevant temporal scope for decision making.

1.1.2 Synergies through infrastructure/service sharing

The second type of synergistic strategy to be developed in eco-industrial parks consists in the sharing of infrastructures and services. The generic labelling of infrastructures and services can consist in a variety of systems and devices as productive assets, utilities-energy generation plants (and the associated transmission systems), industrial water network, waste treatment units, logistics warehouses, site roads and buildings for the most prominent. The specificity of those installations is that it provides a complementary set of more or less homogenous services to the actors. Most of such services are cost components of the actors activities and do not lead to any strategic market advantage. This is a key difference with R&D departments or laboratories which may improve substantially core products or activities market position as in sectorial clusters. At least some efficiency gains over these cost components can be achieved by appropriate cooperation among actors in the eco-industrial park. In case the costs savings achieved are high (or the part of these costs in the cost structure is prominent) then market position can be favoured by corresponding price reductions. Investment and capital costs can be optimized in case of common grass-root infrastructure setting or suitable connection to an existing one.

The economic advantages of such strategies can be decomposed in several dimensions as risk mitigation, investments budget reduction, bargaining position enhancement or capabilities consolidation (economies of scope).

The extent of such gains depend upon various contextual patterns. Each actor faces its own constraints and opportunities in relation with its sourcing strategy, market conditions and technological environment which in combination will affect the value of collective action. Production assets can be networked in order to handle cost reductions (inventory) and risks. On the risks dimension collective networking can be used as a diversification of sources and demands to hedge against risks (Monauni, 2014). Another operational strategy is *resource pooling*. By cooperating for pooling common resources actors can achieve various benefits. Inventories of spare parts (Karsten and Basten, 2014) can be shared and managed to minimize inventory levels. Capacity sizing for installations (design phase) like generators (CHP plants, incinerators, treatment units...) and piping systems for carrying utilities (industrial water, heat transfers, industrial gases) is a key lever to benefit from infrastructure sharing. Regarding energy-utility generation plants or treatment units their *costs drivers* are *capacity* (quantitative) and *capability* (qualitative).

Qualitative aspects determines the technical specifications of the plant and thus will structure the cost of purchased equipments. The quantitative cost driver that is the 'capacity' is of first interest when analysing infrastructure sharing opportunities.

Capacity cost as a value driver

Particular statistical relationship have been estimated by industrial engineers and reported in the academic and educational literature (Ereev and Patel,

2012) following estimation methodologies for capital cost. The baseline formulation of the capital cost estimations rely on a relationship between the capacity of needed equipments and their purchased cost.

The cost is estimated using a *scaling exponent* which allow to derive the (estimated) cost of an equipment from its capacity.

Baseline costs for baseline (standard) capacity from the consolidated databases available in the specialized academic and educational literature (Couper et al., 2008; Chauvel et al., 2001; Max et al., 1991) can be used with the (also) provided scaling exponents to estimate the cost of an equipment in function of its capacity.

In most cases this scaling factor is lower than one meaning that it is preferable (in terms of purchasing cost) to scale-up the equipment rather than buying several ones. After equipment choice and one can recover an estimate of the purchased cost for the whole plant. A distinction is usually made between *inside battery limits* estimates dealing with core process equipments and *outside battery limits* consisting in the estimation of land and yard improvements, roads, buildings but also *service facilities* for utilities generation. The latter is of first importance in industrial ecology. The cost estimation can be performed following the same type of computations but with utilities specific equipments so that the capacity will still be the key cost driver. To have a complete capital cost estimate, those equipment purchasing costs (for both inside and outside battery limits) have to be scaled using additional coefficients to account for other *direct costs* such as delivery, installation, add-ons (piping, instrumentation, electric systems...). *Indirect costs* (or *construction overhead costs*) must also be added (using percentages of the delivered equipment or total fixed-capital investment whose it is part of). In addition to the *fixed capital costs*, the *working capital* requirements must be considered for

an exhaustive *total capital investment* estimation. Working capital accounts for the funds required to finance short term operations. This capital requirement is a *structural* requirement imposed by business conditions and thus is included in the total capital cost.

Capacity choices as a value driver

In terms of infrastructure sharing synergies, capacity choices are driving the capital expenses. Cooperation among actors in the eco-industrial park can allow for substantial gains in terms of capital investment as long as the cost for a given aggregated service or production level can be globally reduced. In fact if the cooperating actors can pool their demands (for a utility or an input production) and in case their demands exhibit synergistic patterns according to their profiles, the capacity cost for the common unit can be lower than the sum of the capacity needed for individual units. The capital investment depends on the capacity required. As long as the equipment costs (and thus the total costs of capital) are concave in the capacity (which is the case for scaling factors below 1) then it is optimal to share a larger unit and not developing several parallel units. The final induced cost then can be shared among participants depending on their contributions to cost (see chapter 3). The key point here to achieve effective gains is the adequation of demand profiles. Indeed in case the sum of demands (loads for the production unit) reaches levels above the maximum among each actors demands (or the corresponding load) then the required capacity under cooperation should increase. For the sake of illustration if each actor would have perfectly synergistic profiles then the capacity required for the pool will not have to be set above the maximal individually required capacity. In the worst case the peak load is attained simultaneously by all the actors so that the capacity

needs will increase dramatically lowering the gains from cooperation. If the cost function is concave in the capacity (and the same applies for each actor) pooling is still synergistic but appropriate cost sharing should be performed.

In addition operating fixed costs can be further splitted among the actors leading to savings in those fixed expenses leading to global cost savings. The same holds for treatment units in terms of treatment capacity setting. Implementing collaborative practices to decrease the peak loads can further reduce capacity requirements. Those strategies are intensive in terms of information sharing.

In case of synergies requiring piping network setting the piping system can be the main capital cost to consider. The main piping *cost components* are purchased equipment, installation costs and maintenance. Purchased equipment *cost drivers* for piping are the length of pipes and their diameter (Hackl and Harvey, 2013). As those drivers are dependent upon the network topography, complexity and density (for length) and throughput (for diameter) substantial gains can be achieved by appropriate technical optimization and common network optimization (Togawa et al., 2014; Chae et al., 2010). Network optimization models in the literature assume fixed parameters for those drivers and then compute the optimal connections within the eco-industrial park with the obtained linear cost specifications. The focus is less "technical" than contributions where the variables of the models are the drivers. Nevertheless some actors might contribute more or less than others to the corresponding costs since their positioning (length) and requirements (diameter) will impact total cost. "Right" assessment of these contribution should be performed in order to properly define contributions in order to implement a cost sharing rule. Installation and maintenance tasks are contracted with some energy or utility service provider thus gains can be done

by sharing this fixed cost among several participants.

Connection of an actor to an existing installation can be done and is a factor of dynamism in eco-industrial cooperations. Connection to an existing (pre-designed) system can raise issues such as *congestion effects* since the capacity can not be sufficient for some periods with an additional participant but it allows to transfer a part of fixed operating expenditures and initial capital investment to the prospective actor. Once again the question of the new entrant's profile is of first importance (Zhu et al., 2010).

Other economic synergies

Order pooling and collective arrangements like purchasing consortia (Essig, 2000) for service contracting or items purchasing can provide benefits (Reinhardt and Dada, 2005). By pooling their orders, collaborating actors can achieve cost reductions through the effect of price discounts on purchases due to bulk pricing policies of item providers stemming from a combination of competition in the upstream market and economies of scale (the upstream cost reductions for service or items provision are at least partly transferred to the collaborating actors due to competitive pressure). Service contracts can also be priced down by contractors since the bargaining position of the pool increases. Such cost reducing practices are due to the interplay between economies of scale and competition for order winning. The latter leading to the actual transfer of those economies of scale to the pool. Thus depending on the market structure, the transfer will be more or less in favor of the collaborating actors. Moreover the effectiveness of economies of scale can also be dependent upon which actors do participate since the need for tailored service or customized items can mitigate those gains. Conditions under which pooling orders or contracting can be a good strategy depends upon

the cost structure for value generation and market structure (pricing policies) for value appropriation. Thus in certain context where both cost reduction is not straightforward (less homogeneity or a lack of coordination) and in which market structure do not incentivize the service provider (or supplier) to price down to match competitors, gains must be limited. Order pooling for service can be used to optimize import/export logistics freight consolidation or warehouse infrastructure sharing. Such practices requires a certain amount of information sharing for coordination (Qiu and Huang, 2013). The logistics service cost structure is characterized by cost components as trucks amortization (capital expenditures) and maintenance costs (fixed operating expenses), workforce(drivers and sorting operators), fuel consumption, taxes, insurances and specific fees for hazardous material transportation for example. Logistics cost drivers are then travelled distance and the number of trucks required. Trucks load and routing patterns are thus the key drivers to be optimized to achieve lower global cost for the cooperating actors. The implementation of such multilateral strategies requires information sharing and collective arrangement setting. Bilateral arrangements for common infrastructure can coexist with multilateral decisions and arrangements. Gains drivers stem from demand or supply profiles (load curves, supply curves) in interaction with underlying (exogenous) cost structures for investments. Implications are raising availability (less risk), decreasing capacity needs (peak), decreasing back-up needs (less over capacity demand), replace back-up source (less costly). Associated interaction costs include intrinsic downside risks of synergies like congestion (less availability) implying more back-up purchasing (less availability provokes back-up quality concerns). It also raises coordination issues and information sharing exposing the arrangement to strategic information retention that can mitigate cooperation and hinder participation.

1.1.3 Industrial symbioses in practice: towards a taxonomy

The aim of a taxonomy :

As we explained hereabove, industrial symbioses can be envisaged as a theoretical construct to identify and evaluate synergies along the use of an asset or a resource. The objects are then generic and do not tell us anything about what kind of assets or what kind of resource might be shared or used in practice and whether or not it has been implemented in real, existing systems. In order to fill this gap and propose a material representation of those assets and resources at stake when dealing with industrial symbioses, we propose a taxonomy of IS practices from the study of real world eco-industrial parks in function. At this point we must acknowledge that this taxonomy aims to be generic enough so as to encompass potential new or uncovered yet forms of symbioses (resources uses or infrastructures). This taxonomy helps to figure out what form can take an IS in practice and what objects can be considered as "usual suspects" for further IS implementation.

Cases selection and relevance

A pool of 25 eco-industrial parks (EIP) is retained for analysis in our study. We indeed limited our attention to EIP cases with available academic (and institutional) references and information on existing symbioses not only projects, like in the Rio de Janeiro case (Veiga and Magrini, 2009). We focus on EIP in which more than 1 symbiosis occurred so as to target eco-industrial networks with both substitution synergies and infrastructure sharing practices that is why Rotterdam harbour case treated in Baas and Huisingh (2008) has been excluded. We thus excluded some cases usually presented as EIPs because

either no referenced and structured information is available, the initiatives did not led to any synergies realization or the realizations are not at an industrial scale requiring investments like municipal synergies in the Hartberg case (Liwarska-Bizukojc et al., 2009). Following this, we retained 25 EIPs to base our investigations towards a taxonomy of IS practices. It should be stressed that 1 over those 25 cases, the Green Valley EIP, is our own case study (Chapter 2). A first observation about EIPs is that it has been implemented in several countries and continents and at different periods. Regarding the territorial patterns of their location, some have been developed in large industrial harbours (Dunkerque, Le Havre, Terneusen, Kalundborg, Ulsan) others close to forests (Green Valley, Kaisersbaracke, Kymi, Jyvaskyla, Uimaharju) while the remaining being deployed in sector specific (or not) industrial complexes (TEDA, Shenyang, Nanjangund, Barceloneta and Guyama, Gladstone and Kwinana, Lubei and Gulf-coast). Agricultural territories are also present (Pomacle and Guitang) as well as municipal/regional wide parks (Monthey Chablais, Kawasaki, Styria, Norkoping-Linkkoping). This variety of territorial patterns demonstrates the applicability of IE inspired concepts to develop innovative partnership in various socio-techno-economic contexts. In terms of dynamics, the process behind their deployment is also variable (see 1.2). In some EIPs, synergies have been developed without any (public) coordinator while in other the influence of such "coordinating bodies" have been important. For this reason, while "EIP labelled" initiatives driven by public actors are easy to identify and then to investigate, some additional IS must already exists but have not been identified yet (Chertow, 2007). For this reason, we advocate further investigations towards IS and EIPs "hidden" developemnts to consolidate the EIP sample available for study in the literature. It is what we have contributed to with our own Green Valley case study (chapter 2).

EIP	Country, date of start/discovery	references
Green Valley	France, 2013	own case (Chapter 2)
Dunkerque	France, 1999	Farel et al. (2016)
Le Havre	France, 1977	Hein et al. (2017)
Pomacle	France, 1990	Thénot and Honorine (2017)
Kaisersbaracke	Belgium, 2006	Bory et al. (2010)
Terneusen	Netherlands, 2007	Spekkink (2013)
MontheyChablais	Switzerland, 2007	Massard et al. (2014)
Styria	Austria, 1993	Sterr and Ott (2004)
Nanjangund	India, 2007	Ashton and Bain (2012)
Kalundborg	Denmark, 1961	Chertow (2007)
Kymi	Finland, 1914	Pakarinen et al. (2010)
Jyvaskyla	Finland, 1986	Korhonen (2001a)
Uimaharju	Finland, 1967	Korhonen and Snäkin (2005)
Norkoping-Linkkoping	Sweden, 2008	Hatefipour et al. (2011)
Gladstone	Australia, 2004	Golev et al. (2014)
Kwinana	Australia, 2000	Van Beers et al. (2007)
Central Gulf coast	USA, mid-1990's	Boons et al. (2009)
Barceloneta	Porto-Rico, 1970's	Chertow and Ashton (2009)
Guyama	Porto-Rico, 2002	Chertow and Ashton (2009)
Kawasaki	Japan, 1997	Berkel et al. (2009)
Shenyang Teixi	China, 2002	Geng et al. (2014)
TEDA	China, 2000	Yu et al. (2014)
Guitang	China, 2001	Zhu et al. (2007)
Lubei	China, 2003	Zhang et al. (2015)
Ulsan	Korea, 2005	Behera et al. (2012)

Table 1.1: EIP list

What is industrial symbiosis in practice: Proposed taxonomy

Using the dichotomy between resource substitution synergies and infrastructure/service sharing synergies, we draw a taxonomy of implemented synergies from the study of the 25 EIP in function in the world (24 from the literature and the Green Valley, our case study). For resource substitution, we classify the objects following their physical nature and the implication it has on the required recovery steps to be performed so as to achieve synergies. Regarding infrastructure / service sharing synergies, we classify the different practices along the function it performs and the involved equipment (or organization) types involved. The resulting taxonomy is depicted in the tables. Detailed description of the EIPs flows and assets are available in the references and schematic representations in Appendix A.

Taxonomy of eco-industrial symbioses (own contribution)

Resource substitution practice	Functionality
<i>Material-Material</i> ▷ Complement ▷ Recycling	conversions during use conversions before use
<i>Material-Energy</i> ▷ Indirect conversion ▷ Direct conversion	fuel production waste as fuel
<i>Energy-Energy</i> ▷ Vector conversion ▷ Direct use	cogeneration heat, cooling water

Infrastructure/service sharing practice	Functionality
<u>Eco-Industrial:</u> <i>Self-Production</i> ▷ CHP plants ▷ Water exchange network ▷ Conversion platforms	supplies: steam, electricity fresh water, cooling, low grade heat CO ₂ , biofuels, Zinc, solvents
<i>Treatment</i> ▷ Waste Water Treatment Plants ▷ Incinerators/CHP boilers	performs and supplies: elimination + sludge supply elimination + ash and heat supply
<u>Other:</u> <i>Purchasing</i>	cost cutting: access price discounts
<i>Logistics:</i> ▷ Inventory pooling ▷ Freight consolidation	resource availability transportation / storage

1.1.4 Modelling tools applied to industrial symbioses

Modelling tools developed and applied for industrial symbioses do perform different tasks using different set of input data (for an extensive literature review, see Kastner et al., 2015). Depending on their structure such tools are useful in different phases of IS implementation. A first set provides informative on resources and needs over a given territory, other contributions propose performance metrics to evaluate some synergies (environmentally and economically) while optimization tools are applied to the design of industrial symbiosis and the related network of exchanges.

a) The issue of Information-Territorial diagnosis tools and information softwares

The willing to plan and develop eco-industrial parks in regional areas induced the creation of a set of quantitative tools tailored to characterize the nature and quantities of available substitution resources deposits and their potential use sinks.

A first theoretical contribution is undertaken in Bailey et al. (2004) who proposed an analysis of quantitative approaches to the analysis of a variety of flows and applied "ecological input-output" model to industrial systems. Arguing that input-output models have been only applied on "monetary" flows, the author adapted this modelling framework to the physical nature of resources circulating in industrial systems leading him to use the concept of "environ" as unit of analysis and proposes the following definition: "Environ analysis is a formal method for completely characterizing the set of flows generated by an inflow or necessary to produce an outflow.". Following this line of inquiry, Sendra et al. (2007) proposed a set of indicators to analyze flows within industrial areas with a focus on the efficiency and system resource importations. A case study has been conducted in Catalonia using 7 information blocs. Those proposed information blocs being "Company organization: economic activity, environmental policy and organization, description of the production processes ", "Environmental problems", "Materials requirements: types of materials, flows and storage" but also "Energy consumption: energy sources and consumption", "Water consumption: sources and flows" , "Atmospheric emissions: composition and flows", "Waste generation: types of materials, flows and treatments" and "Wastewater production: composition, flows and treatments". The author insists on the need (and thus the challenge) of cooperation by companies during the phase of information ac-

quisition.

Regarding France, to the extent of our knowledge, 4 main tools have been developed. Julien-Saint-Amand and Le Moenner (2008) explores the limitations of the PRESTEO tool which is based on input-output matching methodology developed by a compagny (Systemes durables). The users must fill their own input and output tables and the software operates a matching whose outcomes are displayed to users to help them identifying potential substitution synergies. Application of this tool in the Geneva regional area is detailed in Massard and Erkman (2007). The second initiative of this form, the COMETHE¹ project, proposed a synergies deployment framework based on experiences conducted in 5 territories in France (notably Dunkerque Harbour) from 2008 to 2011. The aim was first to gain research insights on industrial symbiosis and second to propose a set of guidelines to help practitioners (EIP planning managers or companies) to implement symbioses. Guidelines are publicly available in 4 interlinked methodological modules on "Analysis of territorial potential", "Study of conditions of achievement of eco-industrial synergies", "Implementation scenarii definition" and "Strategizing industrial symbioses for a sustainable development of territories". Nevertheless, few informations are available on its actual use by practitioners. At the initiative of French agency for energy efficiency (ADEME) and Tarn-et-Garonne industry council (CCI) the "Act'if" platform had been set in 2013. This tool aims at developing IS in France using a Geographic Information System (GIS) to provide a map of resources and potential users on a given territory. Act'if is a web platform developed by the Tarn-et-Garonne industry council leveraging the data on regional companies and public utilities to identify and make available information on resources, uses and needs of any

¹Conception d'Outils METHodologiques et d'Evaluation pour l'ecologie industrielle

actor in the region. This platform can be used by local representatives and policy makers striving for synergies to browse data and identify potential projects. Mapping of resources (and needs), synergies evaluation and project support are conducted by the regional managers of the tool.

On academic contributions, an integrated quantitative tool encompassing information gathering and architecture design has been developed by Hein et al. (2016). The aim of this methodology is on one hand, to complement the (rather scarce) literature on (practical) territorial diagnosis tools by proposing a generic framework and on the other hand, to offer an integrated tool designing EIP architectures from suited data gathering and treatment.

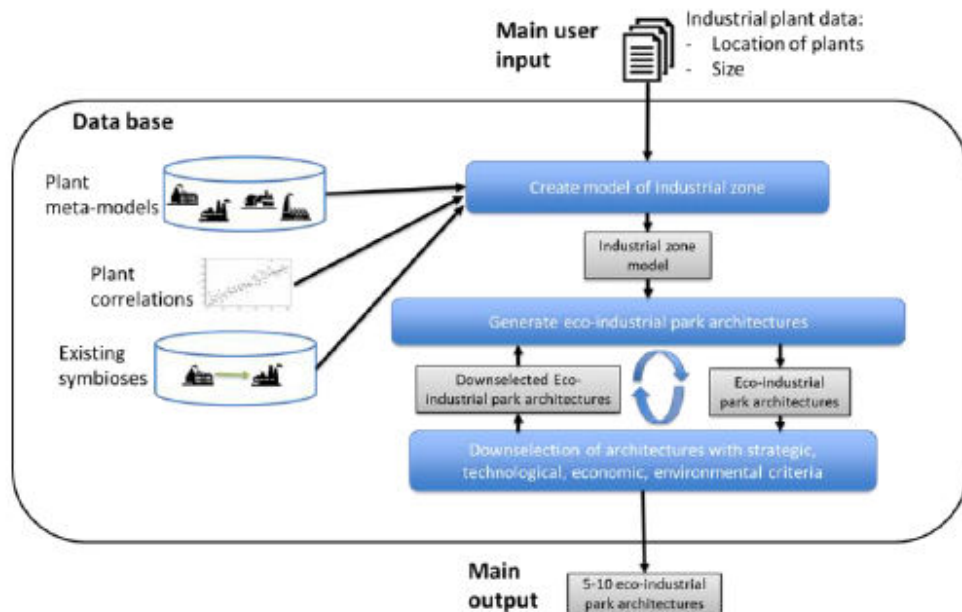


Figure 1.1: Methodology scheme (From Hein and al.,2016)

The original strategy adopted is to construct estimation on resources and sinks data using plants' "meta-models" leveraging correlations found in process engineering literature to overcome the issue of direct data collection from

companies. Then an optimization model is formulated and generates several EIP architectures along 2 dimensions, the economic value (using Net-Present Value) and the environmental one (through Life Cycle Analysis).

This methodology has been applied to the Kalundborg EIP in order to test its outcomes on a real world instance. In another recent contribution, Cecelja et al. (2015) developed an interactive web-service dedicated to the identification and deployment options of industrial symbioses. Users can upload their information and request while practitioners can enhance the set of applicable technical solutions to iteratively define an applicable solution to implement the resource-sink matches generated in the embedded software. An application targeting small and medium businesses is proposed in a local area in Greece.

b) The issue of evaluation-Performance index metrics

Generic techno-economic metrics

Implementation of synergies should be economically sound for actors investing in equipment suited to realise resource substitution so that a first set of indicators used in the evaluation of IS opportunities are classic economic criteria that we briefly introduce. The widely used *Net Present Value* (NPV) accounts for the actual value of the future (deterministic) *(free)cash flows* generated along the asset use once deducted the initial investment. The value of future cash flows is *discounted* in order to take into consideration the time value of money. The discount factor must be suitably chosen according to the financial structure of the investment funding like acknowledged previously (either interest rate, equity cost or weighted average cost of capital). *Adjusted present value* can be useful when analysing the impact of financing in investment valuation due to *tax shield*, the presence of *subsidized loans*

(priced below the market rate) or floatation costs. Amortization must be removed from the computations of value generated by the investment since it would otherwise be accounted twice (as the initial investment cost and as an operating expense in the operating income statement). *Expected net present value* can be used to evaluate investment if cash-flows are assumed to be uncertain. NPV perspective supposes a fixed time horizon that is usually set as the asset's lifespan. On a cost analysis perspective, one can assess whether or not the substitution synergy opportunity is beneficial regarding cost savings. At this point NPV can also be used by considering the savings over alternative option as economic gains. Another way to deal with this analysis is to choose a cost perspective and thus account for the net savings achieved by comparing the situations according to given cost measures. The *annualized cost* is a synthetic cost indicator which aggregates the annual operating costs to be incurred in the option under study with its annualized fixed-capital costs using an *annualizing factor* computed according to assumptions on the number of years the asset will be used and the corresponding discount rate (or cost of capital). Annualized cost allow to compare options with different lifespans.

Environmental metrics:

On the environmental side the evaluation metrics proposed in the literature merely have 2 different target that is resource conservation and pollutants emmission reduction. A recent literature review performed by Valenzuela-Venegas et al. (2016) proposes a comprehensive synthesis on this topic. Among the key contributions we can highlight Zhu et al. (2010) who developed a framework to assess the economic and environmental impact of the entry of a firm within an EIP. Indicators are splitted in "park-based indicators" and "enterprise-based indicators". The former beeing composed of

3 aggregated measures (degree of "matching with industrial chains", "park carrying capacity" and "park environment performance improvement") and the latter comprises 4 ("eco design", "resources utilization", "pollutents production"). Each of those sub-indexes being accounted for using different (mostly per unit of value added) metrics. We can also indicate that the question of IS impact on pollutants or CO₂ emissions have been studied in several contributions. Hashimoto et al. (2010) analyze the impact on CO₂ emissions of implementing IS in the cement industry. They adopt a life cycle analysis so as to account for every operations its emissions (waste disposal, cement production and transportation). CO₂ emissions and its linkages with other performance metrics (notably economic ones) are also studied in Paquin et al. (2015). Such linkages are also studied in the IS tailored eco-efficiency framework developed by Park and Behera (2014) which accounts for economic performance (value-added) and a composite environmental performance along 3 dimensions ("resource consumption", "energy consumption" and "CO₂ emissions"). Most recent contributions (thus not reviewed by Valenzuela-Venegas and al., 2016) towards multi-dimensional assessment of IS is available in Zhao et al. (2018a). In this contribution indicators pertaining to the environmental dimensions are associated with economic and social ones and include, in addition to per-unit of economic value added indexes, "recycling rates" for waste water and industrial waste. A comprehensive benefit evaluation of EIP based on a multi-criteria analysis is further proposed in Zhao et al. (2018b) on the basis of the former article.

c) The issue of design-optimization models

Modelling an eco-industrial park requires first to define a set of actors. Actors are characterized by a set of attributes and act as decision makers in

the park. The global context in which those actors will interact also has to be carefully represented by contextual parameters. Actors' attributes will be set and affected by the modeller in order to represent the eco-industrial park structure. In a design perspective, influence over a criteria is exerted by performing decision making on some attributed control variables. Decision making supposes access to relevant information in order for the agents (or the designer) to state their preferences over their control options. Decision steps structure the way information on systems' state evolution is taken into account in decision making. When dealing with operations planning problems supply chain modelling use stochastic (or deterministic) multi-period settings involving fine-grained ongoing adaptation decisions focused on optimizing planning procedures and/or controls (sizing and sequencing). It is worthnoting that "steps" and "periods" are different model elements but they can interact. A decision made at a particular step might be irreversible for some periods of the problem horizon. Steps is associated to the informational and decisional patterns of the economic situation under study. By architecting those steps the model focus is specified. Regarding this last point the set of planning policies that are analysed and assessed with such models defines a set of tactic options (the policies) but the decision points associated with the considered uncertainties belongs in the operational level and not into the strategic one. The planning policies do frame the lower level decisions (usually production rates or ordering). Planning problems resolution requires advanced optimization techniques from operations research like dynamic programming or tailored heuristics.

This class of approaches is used in the supply chain literature on inventory control policy, dynamic lot-sizing or operations sequencing but not in industrial economics unless the multiple-period timing is necessary to adress some

strategic decisions at the difference of the tactical and operational point of view of supply chain literature. Few models of this type do target explicitly IS (Teo et al., 2017) but can be a suited tool to help a better matching of supplies and demands in the irregular context of resource substitution synergies. This element can allow for richer modelling of eco-industrial park's context dynamics and uncertainties. Testing variations in its patterns can be informative on some problem aspects or solution evaluation like their robustness or stability of EIPs architecture (Chopra and Khanna, 2014; Wu et al., 2017; Kuznetsova et al., 2017) . Nevertheless the number of periods considered will be important for the model focus only if its structure interacts with the abovementioned decision steps which drive the investigations. Rich interplay between decision and information displayed over a detailed time horizon is somehow over the scope of economic models and rather one of the key investigation driver in the supply chain literature. Regarding design tools applied to industrial symbiosis and eco-industrial parks, the cost minimization perspective and investment profitability can be used as economic assessment approaches. Several models have been proposed in the literature to optimize a network of eco-industrial exchanges in a network optimization perspective (see notably the extensive literature review by Boix et al., 2015). Network design indeed deals with strategic long term decisions but at the difference of economic literature the problem under investigation is combinatorial complexity of solutions rather than (inter) organizational strategic interaction.

Following the survey of Boix et al. (2015), the key applications of optimization models for the design of IS in EIPs are steam/energy and waste water exchange networks. A model minimizing park energy cost through the use of waste heat is available in Chae et al. (2010). Regarding waste wa-

ter exchnages, Lovelady and El-Halwagi (2009) developed and solve a water cost minimization problem including waste water sources, sinks and interceptors. Boix et al. (2012) analyse different network types in EIPs (location and ownership of regeneration units for contaminants elimination) along a bi-objective formulation dealing with freshwater flowrate and regeneration units inlet water flowrate. In a related contribution, the effect in terms of solution feasibility and required network evolutions (connections and regeneration units) of variations in the contaminants quantity is studied (Montastruc et al., 2013). Water quality issues are also enlightened in Tiu and Cruz (2017) who developed a goal programming formulation of waste water network design in order to handle simultaneously the conflicting economic and environmental criteria (freshwater consumed and lower quality water released). Regarding uncertainties, Aviso (2014) investigates the robustness of the designed water exchange network considering different potential scenarii regarding the number of EIP participants and their characteristics. This model determines the network minimizing freshwater consumption over the (probabilistically distributed) scenarii. A set of additional formulations of the robust water exchange network are developed in Kolluri et al. (2016). In a recent contribution, Teo et al. (2017) notably proposed a model integrating waste water flows with steam production and distribution with a "centralized utility system" for the EIP. The model objective is formulated using a fuzzy approach (degree of satisfaction) to encompass economic and environmental criteria. The multi-level aspect of the modelling of EIPs is studied in Pan et al. (2016) who proposed a 4 level framework for designing exchange networks in EIPs integrating the multiple scales at stake from the very detailed technical process modelling to industrial network-scale economic criteria. On "horizontal" complexity, Afshari et al. (2017) developed an approach to de-

sign multiple items exchange networks in EIPs and assess the impact of the introduction of parameters uncertainty on the optimal solution.

The issue of individual actors' satisfaction received increasing attention in the recent literature on the modelling on EIPs and IS. Using the "mathematical programming" (Linear programming) formulation of a cooperative game solution developed in Maali (2009), Tan et al. (2016) explicitly considered individual actors' objectives in a satisficing perspective. Following Maali's solution concept, average individual contributions to coalitions value are used to weight the allocation of value among actors in the linear program. Andiappan et al. (2016) use a coalition-based reasoning to determine the value contributions brought by actors within an EIP and defines the admissible parameters value changes that do not affect the stability of coalitions ("the stability threshold"). Another contribution taking into account actors' satisfaction is the fuzzy optimization formulation developed in Ubando et al. (2016). A fuzzy mixed-integer nonlinear programming model is build so as to define the network of exchanges (partially) satisfying the global EIP footprint constraint as well as each actors' minimal profit and output constraints. This contribution adopts a satisficing perspective to balance each actors' outcomes while dealing with the optimization of a (derived) global criterion. Actors' preferences over each EIP evaluation criteria are modelled using Analytic Hierarchy Process (AHP) and then introduced in a multi-objective optimization model so as to generate EIP exchanges networks integrating actors objectives in Leong et al. (2017).

This set of recent contributions indicates a willing of the scientific community to explicitly investigate the influence and importance of individual actors preferences (and satisfaction) in EIPs. Following an economic perspective, the actors' attributes consist in objective functions derived from preferences

over consolidated criteria mapped with the state of the system (the eco-industrial park and its environment). Strategic decision variables influences on criteria are dependant upon their association with both contextual attributes of the eco-industrial park environment and their interplay with controls mastered by other decision makers (decision to supply, to order items, to comply with rules ...) thus partly shaping the systems structure and resulting state. Both economics and supply chain literature look at strategic level decision making. Economics study prices determination and sourcing strategy (demand structure) taking into account costs structures when network design perform the reverse by optimizing costs taking as given sourcing strategy (set of suppliers and their prices) and market conditions. This distinction between the supply chain literature and the industrial organization one thus stands in the nature of decisions over which preferences are defined. It follows that the economic approach will then be our line of inquiry towards the study of transactions.

1.2 Socio-economic vision of industrial symbioses:

Eco-industrial parks, roles and networking

a) Eco-industrial parks and other forms of "green" networked businesses: towards a definition

The literature on the developments of industrial ecology principles erected and discussed about the conceptual content of interrelated concepts of industrial symbiosis and eco-industrial parks. Moreover some contributions made a distinction between those forms of partnering or collective strategies and other notions of networked businesses or collective practices in the in-

dustry. Following those conceptual discussions we propose a definition of an eco-industrial park. Exploring the definitions found in the literature leads to figure out that even if the concept might be close to other, key differences must be highlighted. First we explore the differences between industrial ecology inspired networks and other business networks concepts. We then analyze their differences with other forms of business networks depicted in the literature. Literature proposes several definitions of EIPs. Lowe (1997) who stated one of the first definition of an EIP insists on its nature (a set of actors) and objectives (environmental and economic performances): "A community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials." In this definition, the collaboration modalities are not well specified so that authors precised the content of such a collaboration insisting on resource exchanges leading to consider the concept of Industrial Symbiosis (IS). Chertow (2000) in her seminal contribution on IS states that: "Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials,energy, water, and/or by-products". Lowe (2001) adapted his own definition and added a geographical notion of estate stating that: "An eco-industrial park or estate is a community of manufacturing and service businesses located together on a common property. Member businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realize by only optimizing its individual performance". In this new definition the advantages of collective action might overcome the

individual possibilities of resource use optimization. This new geographical feature have been considered by Desrochers (2002) when he states his own definition, now insisting on the distinctive role of physical exchanges in the definition: "An eco-industrial park (EIP) is a community of companies, located in a single region, that exchange and make use of each other's by-products or energy". Gibbs and Deutz (2005) do insist again on the physical exchange feature that must be distinctive since EIP are associated with Industrial Ecology concepts: "In total, then, there is substantial debate over what defines and constitutes an EIP. While we are sympathetic to the argument that these need to develop over time through a variety of strategies, we would also argue that if we are dealing with the concepts of industrial ecology and symbiosis, then waste and energy exchanges and some degree of inter-organisational networking must be present to earn this definition", leading them to consider that: "Eco-industrial parks (EIPs) are based directly on industrial ecology concepts-they aim to increase business performance while reducing pollution and waste through encouraging interchange between co-located firms". Mirata and Emtairah (2005) proposed to analyze Industrial Symbiosis Networks: "a collection of long-term, symbiotic relationships between and among regional activities involving physical exchange of materials and energy carriers as well as the exchange of knowledge, human or technological resources, concurrently providing environmental and competitive benefits ". Those definitions are in fact related to what we consider as an "Industrial symbiosis". This concept have been questioned by Boons et al. (2011) who states that "industrial symbiosis can be usefully conceptualized as a process rather than a state of affairs.". Following this Chertow and Ehrenfeld (2012) proposed that "[...] we have come to use the term industrial symbiosis in two ways: (1) as the broad name for the branch of industrial

ecology that seeks to understand the development and functioning of inter firm resource exchanges, and (2) as an inclusive descriptor for all arrangements where enterprises exchange outputs that, in the absence of a customer, would normally be discharged to the environment and hence become treated as environmental externalities. These resources include reused water, recovered energy, and material by-products-categories often called wastes (as in wastewater, waste heat, or solid waste)". Lombardi and Laybourn (2012) questioned further in detail this concept notably Chertow's first definition and the geographical dimension of IS: "IS is not essentially localized waste and by-product exchanges, nor should it be confused with agglomeration economies or industrial clusters where geographic proximity is a necessary condition. We explicitly negate the geographic proximity argument in favor of one that is rooted in innovation and networks for knowledge sharing, resulting in, but not driven by, improved efficiency in the use of materials.". Their point is mainly to state that a narrow vision of I.S as induced by the former definitions would reduce its potential as a sustainability improving tool because it hinders innovation oriented practices so that the problem is not the definition itself but rather its consequences. Regarding its links with the "cluster" concept, Deutz and Gibbs (2008) proposed that EIPs are the realization of a specific clustering strategy based on environmental recognition of benefits induced by by-product exchanges: "[...]more significant differences between EIPs and other clusters are an awareness of the environmental benefits of agglomeration [...], awareness of economic benefits in environmental practices, the nature of the envisaged transactions between cluster members and the sources of cost savings if those transactions were realised. The physical exchanges characteristic of an industrial symbiosis cluster are not a trivial variation on the clustering theme."

As a result we might see eco-industrial parks as the "actor community" part of industrial symbioses that is its socio-economic dimension.

In order to state a synthetic definition of what is an EIP in our work we must also differentiate it from other form of networked businesses. In line with the remarks rose by Lombardi and Laybourn (2012), authors investigated the key distinctions between EIPs and existing concepts of networked businesses. First, EIP might be differentiated from green-business cluster or "eco-industrial networks". Patala et al. (2014) identified 4 different types of such networks aiming at improving the sustainability of industrial production. Among the 4 forms they consider "industrial symbiosis networks" as one particular form whose characteristic feature regarding environmental impact is to reuse waste as resources. This form thus differs from "Sustainable supply networks" (life cycle based designed supply chain), "Environmental issue networks" (mitigation of pollution related issues through collaboration) and "Environmental solution networks" (eco-innovative solution development with a core technology). In the same line, Agarwal and Strachan (2006) proposed a synthesis on the forms of "eco-industrial developments". "By-product exchanges" is one modality among others. The other forms identified are "recycling business cluster", "environmental technologies companies", "companies making green products", "industrial park designed around a single environmental theme", "park with environmentally friendly infrastructure or construction" and "mixed use development" (including residential estates). Moreover EIP concept also differentiates from various "industrial parks" forms. Heikkilä et al. (2010) proposed a classification of such "industrial parks" as a part of their multi-companies sites risk management framework. In their definition "industrial parks" are differentiated from "industrial areas" because of the ties induced by the sharing of

some infrastructures, buildings and mutual risk exposure. Following their classification "industrial parks" can be "science parks", "technology parks", "innovation centers" or "business parks". From our point of view, the geographical notion of co-location within an industrial estate is not essential in the nature of EIPs distinctive features. As denoted in Harper and Graedel (2004) "despite common usage of the term "eco-industrial parks", it is important to note that industrial symbiotic relationships do not necessarily exist within the confines of a park".

Synthesizing all those theoretical discussions we finally propose to define EIPs the following way:

An eco-industrial park is an open community of actors striving for economic and environmental efficiency of their production and use processes leveraging shared assets and using waste and by-products as substitution resources.

b) Eco-industrial parks dynamics and development: a taxonomy

The way EIPs are developed and evolve has received attention in the literature on Industrial Symbioses and Industrial Ecology. In a recent contribution, Boons et al. (2017) proposed a structured framework to depict the IS deployment patterns investigating several cases of EIPs in the world and the literature. The authors proposed 7 basic form of IS deployment. Those 7 forms can interact during the life-cycle of the I.S and some might be replaced by other. This framework is based on the way different kind of actors interact in EIPs leading to developp IS.

The first form which have been acknowledged as the most fequently observed is "Self-Organization". In those cases (notably Kalundborg) exchanges emerged spontaneously from independant private initiatives of actors without a "co-

ordination body" intervention.

A second form identified is denoted as "Organizational boundary change". Here exchanges are generated between actors who were formerly merged into one entity (see the case of Guitang Group). By re-organizing its activities and cease capital to external investors formerly internal synergies become inter-organizational symbiosis.

The intervention of a dedicated "coordination body" to foster IS can get several forms that delineate other identified structures. "Facilitation-Brokerage" consists in a form in which a coordination body provides forums and performs networking in order for the interested actors to further explore by themselves the existing opportunities.

Another form of facilitation, "Collective learning" operates differently. In that structuration, the coordination body does acquire and gather information on potential synergies on a given territory and then proposes symbioses opportunities to actors. The facilitator maintains the IS information and updates incrementally the status of various synergistic opportunities.

Whenever the facilitator does participate actively in the implementation of the exchanges, we face a "Pilot facilitation and dissemination" form of development. This form is characteristic of Korean EIPs (notably Ulsan). The role of the coordination body or facilitator is to act as a super-consultant who provides information on potential synergies achievable but also participates in the planning of the final implementation of synergies.

The 2 last forms identified and conceptualized are "Governmental Planning" and "Eco-cluster development".

The former involves participation in financing, planning and design of public authorities to develop synergistic exchanges. This pattern is emblematic of Chinese EIPs which are fostered by proactive state involvement. Regarding

"Eco-cluster development" the synergies are embedded in a set of measures aiming at developing or re-developing industrial areas in a more sustainable way.

In a recent contribution Bellantuono et al. (2017) characterises further the organisational forms of EIPs and their relationship with implemented sustainable practices. In their framework the organisational dimensions characterizing EIPs are "Development process", "Existence of an anchor tenant", "Governmental support", "Heterogeneity", "Cooperation among companies", "Cooperation with universities and research centres", "Cooperation with governmental agencies", "Shared information system", "Shared support services". For each item some modalities are given from the literature.

This last framework can complement the former to have an in-depth dynamic characterization of EIPs forms.

To summarize we saw that IS dynamics is related to potential exchanges and actual matches and their relative attractiveness for individual actors whose commitment is a prerequisite for network consolidation and value generation. We thus view IS dynamics as the process of passing from virtual EIP network to concrete transactions through a sequence of commitments and divestments from individual actors. To characterize a dynamics one must specify its spaces. IS evolves in the actors space (participants), the outcomes space (economic and environmental effects), the operations space (functional configurations). Actors shape the objectives correlations and tensions (incentives) while the outcomes space the objectives level. Operational space determines a set of constraints (resources and assets available) that will interact with actors objectives and thus influence IS system behavior. Entry and exit into the EIP "community" must not be confounded with commitments

and withdrawals in the "operational" IS exchanges. Firms' or public plants strategic location does affect the EIP as a community (interest). Location in an territorial community can be more or less dependant upon exogenous reasons like global supply chain networking decisions. Advantages offered by EIP to its incumbents can therefore favour in some cases the EIP development (Green Valley, Terneusen ...). The virtual (or potential) network will shape the IS deployment pathways due to rent seeking behavior of actors and institutional capacity building and trust reinforcement. Induced perspectives are different than what it is from concrete commitment since it involves different conditioning of behavior and decision making (sunk costs, learning, contractual/technological lock-in...). In some sense IS implementation reduces ecosystem entropy. When implemented an IS exhibits less degrees of freedom than "on-paper" projects under discussion in the EIP. Investment cycles, priorities misalignment (preferences) and funds availability can cause sub-optimal configurations to emerge. Investments priorities matches drives IS implementation. Exogenous factors can either facilitate those matches or create mismatch regarding actors' priorities. Implementation and optimiza-

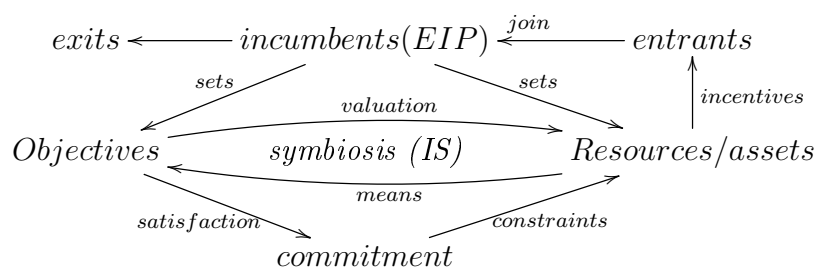


Figure 1.2: IS dynamics in EIPs

tion of those value-adding strategies is envisaged in a systemic approach to benefit from positive externalities in the eco-industrial park. As one of the main issues in the practical implementation of the synergies is quality and

quantity concerns, suitable networking and cooperations in the eco-industrial park must strive to allow *access* to the resources. Resources access enabling needs competencies (assets and knowledge), means (financial provision, adequate technologies and flows) and coordination (information sharing and collective decision making).

An eco-industrial park can be therefore considered as a decentralized *value chain*.

1.2.1 The process of industrial symbioses implementation: economic roles towards transactions

Characterization of actors' economic roles

Functional analysis of the eco-industrial park leading to identify individual contribution to the systems wealth (the value chain) and the associated cross-effects (externalities) has to be performed. Individual actors can benefit from the industrial symbioses according to their fonctionnal positioning in the value-adding system by adopting strategic behavior. Functional roles then must be defined properly in order to launch symbioses analysis. Sets of actors and functions will shape eco-industrial park structure. Propositions have been formulated by industrial ecologists (Ashton, 2009; Liwarska-Bizukojc et al., 2009) in drawing parrallels between natural and industrial eco-systems functioning. A limitation of those parrallels lies in the endogeneity of symbioses because of in the industrial (human) context, symbioses are set-up by synergy seeking *decision makers*. Stakeholders roles in eco-industrial parks projects have been investigated in Brulot et al. (2014) and the proposed characterization relies on 3 attributes from the view point of sociological framework from Weber and Marshall across the dimensions of *Power, Legiti-*

macy and *Interests*. The authors point out that the coordination rules must be considered as endogeneous to the process of planning an EIP initiative. Roles are defined along *decision rights* and *capabilities* to exert *control* over assets, resource flow management, service provision, information gathering and processing.

The role and position of each actor in the eco-industrial park do have an impact on value creation, market structure and thus strategies adopted. Market power and bargaining positions must be understood. The role of brokers and bridging actors shapes the network. Firm organization might play an important role since a more decentralized organization (business unit) is more acute to incentivize IS and limits projects competition for funds. It follows that sub-sets of agents can therefore implement collective strategies by forming coalitions in order to enhance their global positioning in the system they are part of. Such collective action must be sustainable and supported by stable mutual gains from acting collectively. Coordination must allow to achieve best outcome of collaboration and the sharing of this value have to be realized by consistent internal arrangements. Failure to find such arrangements (value sharing) or misalignments mitigating gains can limit the incentives to participate in such collective action.

Adopting a systems perspective, we propose to define some functional tasks that have to be done to enable symbioses or improve their value.

Resource generation (Sources)

Substitution resources are originating from core activities of actors in an industrial eco-system that generate waste streams which must be adequately treated and/or disposed off. Collecting those unused streams by diverting wastes from their original destination (like landfill) for recovery of valuable by-products to be used by other actors processes is a *substitution strategy*.

By-product and waste can be suitable as raw materials for production (fly ash and cinders for cement production), as fuels for energy generation (organic waste) or as a utility (process water and fatal heat). Over the environmental interest of limiting the use of virgin natural resources and final waste discharge, substitution can be economically sound. For the source actor in the best case, it corresponds to a decrease in treatment costs and a revenue generation at once.

Resource use (Sinks)

The counterpart of sources in exchange are referred as sinks. The sets of sinks are composed of potential users for a given resource. Sinks will use the provided resource in substitution to an alternative one usually supplied by economic actors that are not part of the eco-industrial park itself (internal market) but rather at its frontier. Economic conditions at stake for symbioses depend upon those "external" actors (external market). Cooperating to implement exchanges of recovered resources between sources and sinks changes the input mix of the latter in a mutually profitable way (otherwise the substitution is not adopted). If costs for recovery and transfer operations are sufficiently low (at least lower than prices charged by the original supplier) transaction can be mutually profitable due to a non-empty *bargaining set*. It is worth noting that the strategic attitude of the "external" supplier may hinder such arrangements if he can credibly undercut prices. A consolidation process occurs when complementary flows or assets have to be used together to generate value or to enhance global value through positive externalities. This is the case in chemical industry in which the platforms seek to match complementary industries in a given site in order to benefit from infrastructure and service sharing synergies. Strategic position improvements are also achieved in this case by integrating the supply chains. Consolidation

thus generates *network externalities* by associating complementary assets and competencies owned and mastered by the actors. *Processors* and *conveyers* actors perform transformation steps that are required to allow a qualitative access to a resource (energetic use of waste materials in incinerators). Processors master technical capabilities and have control over assets suitable to apply value-adding operations on source resources for subsequent sink use. Likewise conveyers, they are part of an eco-industrial park embedded supply chain. These actors are characterized by their throughput. A slight difference between the conveyers and the processors is that the formers transfer value whereas the latter generate value. Ability to transfer value from a source to a sink in a middleman positioning is induced by their core competencies and technologies or by legal context (waste regulations). Higher efficiency in performing the task can also warrant their direct participation (third party logistics providers-3PL or energy service providers) leading to avoid direct execution by upstream and downstream actors.

One of the specific features of the industrial symbioses business context is the irregular patterns whereas core activities require stable resource quality and quantity. Accordingly flows of substitution resources can be insufficient to match participants' requirements.

Massification can therefore foster the implementation of exchanges. This task supposes collaboration and surplus sharing among actors all contributing individually to the aggregated flow (of supply or demand). A critical mass of trade ensures the recovery of investment costs. In addition, this strategy can be cost efficient if investment cost is submodular in the total quantity. Massification can be performed by multiple bilateral contacts and arrangements if a sink accumulates supplies from various sources. Massification of flows (supplies or demands) will be interplaying with *pooling*

strategy used in sourcing risks management. Demand profiles complementarity between the actors that pool resources or requirements can be used to minimize the required inventory of resource needed within the pool. An issue is then to deal with the identification of potential hazards. It can increase the transaction costs of setting a pooling related arrangements between the collaborating actors. Pooling advantages consist in risk reduction and gains from infrastructure sharing for a given level of service if the cost function is submodular. *Diversification* strategies in eco-industrial parks can be very important since supply and demand quantities can be highly uncertain as well as quality concerns. Consumers can achieve improved supply reliability by aggregating different sources. Volume irregularities and quality troubles can be hedged by simultaneous exchanges. In terms of sourcing strategy, the access to substitution resources from diverse sources can also be considered as hedging on prices. In the suppliers view point, diversification of clients induces stable and reliable demand for by-products and thus secures global trade volume for investment recovery.

IS evolution from exogenous and process endogenous dynamics

External factors (regulations, global firm strategy, technological changes) reshape core activities patterns and thus generate objectives and limitations to overcome while dealing with IS transactions. Feedback loops reinforce or weakens IS prospects or actual cooperations (Figure 1.3). We argue that the IS development is thus a process composed of positive feed-back loops and mechanisms as well as negative feed-back loops and mechanisms that might be understood. Path dependence is stemming from "lock-ins" that are quoted as key issue in IS (Korhonen, 2001a; Boons et al., 2011). Lock-ins related to the intertemporal ability to trade-off structural and operational changes. Its drawback is that firms may value more adaptability regarding

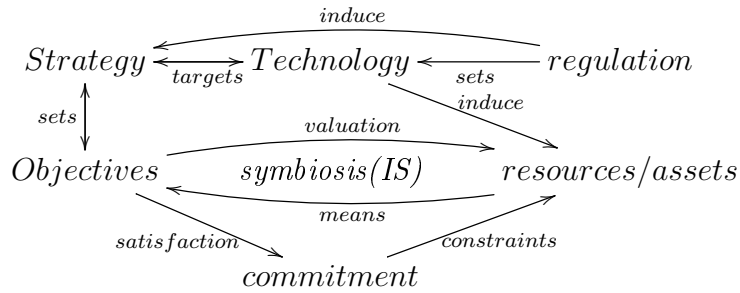


Figure 1.3: External factors and IS

their core operations from which sub-optimality is costly (in terms of optimal) against more or less uncertain profitability of minor by-product or sharing symbioses since it has a priori less value than full flexibility for core activities. Firms and decision makers actually worry about being ex-post incentivized (due to ongoing IS participation) to act sub-optimally regarding global best decision (the best decision without IS). Thus decision makers trade-off this sub-optimality with expected gains from IS before the decision has to be made for example because of large penalties to be paid to the partner if the supply of by-product is not performed. Decision makers adopt a "wait-and-see" attitude towards (core product) market changes, technological changes or regulatory conditions that hinders commitment to IS associated contracts². On the reverse, some IS might be seen as substitutes to core activities (see Green Valley, chapter 2) and thus gain another status in businesses strategy. It is the case for declining industries (paper, steel...) for which IS does not represent only a valuable project but a shift in the portfolio of activities. It is worth noting that in some cases a mix of those reasons applied but it pertains to the differences in maturity of each EIPs. Successive IS development can be nested following an "anchoring

²Long termed and rather complex to safeguard value generation and assets as we show in Chapter 3

process" Sun et al. (2017) that is constructive with high interdependencies. While in what we acknowledge as "Mosaical" IS development the dynamics is more conservative inducing lower dependencies over IS implementation and functioning. Which mechanisms underpins such developments? In nested development, new activities deployment through symbiosis setting occurs. Additional activities development is fostered using IS principles. Such an evolution being due to a mix of external factors and internal enhancements (learning curves, trust, knowledge sharing-"flow", knowledge acquisition-"stock", practices adoption-better coordination). In mosaical development existing activities reinforcement through symbiosis setting are more oriented by cost savings argument (far from core activities value). In that case external factors can have a quick influence notably regulatory change (in line with I.E or not) as well as longer term moves like technological change (global or subsequent to either market conditions or regulations). To summarize, in EIPs there is an interplay between driving factors that will affect capabilities, tradability, resources volumes, quality and actors objectives and priorities defining preferences over transactions to commit to.

Process representation: from I.E initiative to I.S implementation

So far we have considered industrial symbioses as networked devices (flows, assets) and we have emphasized the role of actors as "decision makers" in the process leading (or not) to implement projected I.S. We can thus propose to represent the process by which idea goes into reality as follows (Fig.1.4). The process structure encompasses upstream and downstream phases each associated through elements constituting sub-processes. In the upstream part "interested actors" launch an eco-industrial initiative, in a particular context (economic troubles, environmental concerns, regulatory pressure ...) on

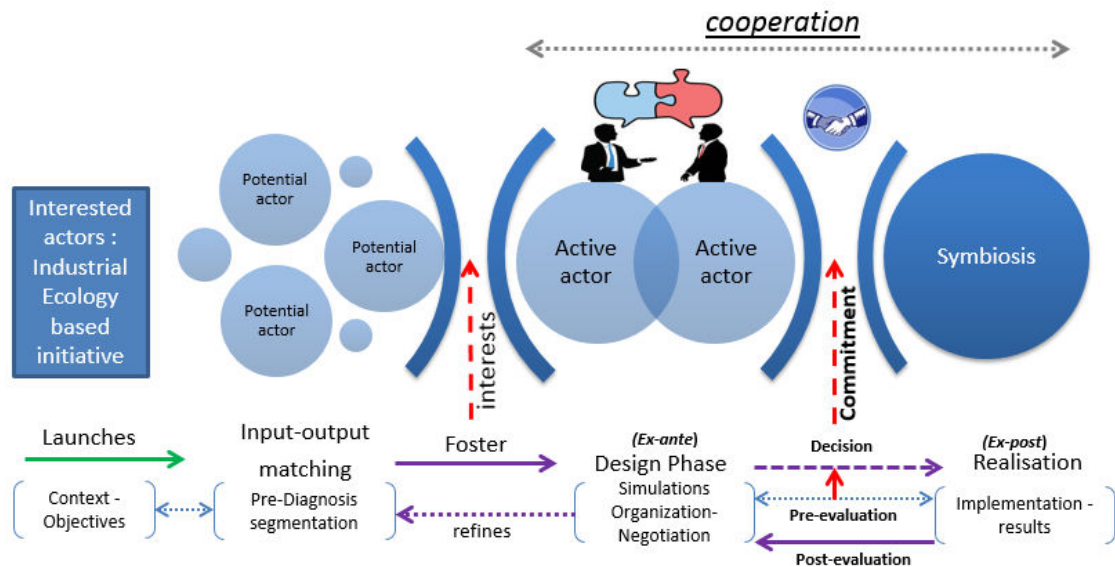


Figure 1.4: I.S implementation processes

the basis of their objectives. While matching resources with needs, "potential actors" are then identified (and segmented following their roles) using diagnosis tools. To deepen the study of opportunities raised and enter a "design phase" of infrastructure sharing and flows exchanges potential actors must commit to exchange further information and should be interested in doing so and adhere to the symbiosis project. An appropriate diagnosis tool might help to achieve this first step towards cooperation. Formal cooperation begins whenever interested actors do exchange more accurate information on their resources, needs and their own internal processes (both technical and organisational) so that actors become "active". In the design phase, active actors share information so as to simulate outcomes generated by several technical and organizational configurations (notably contracts). Informations exchanged during this phase can help (or lead to) adapt both results and procedures of the diagnosis step. Design phase thus performs a

pre-evaluation of what could happen if the solution is retained and committed to by each actor. In order to trigger mutual "commitment", the solution co-constructed in the design phase must be satisfactory for each actor. The decision to commit lead to enter the last phase of symbiosis implementation that is its effective "realisation". Challenges and successes pertaining to the realisation of the symbiosis lastly feed-back the design phase patterns and so the whole process.

1.2.2 Modelling and analyzing eco-industrial parks

Sociology approach

EIP is a set of actors fulfilling objectives. Analysis of the EIP concepts and its real world instances have been extensively proposed in contributions from sociology. Sociology analyses industrial symbiosis as a process which is a theoretical unit of analysis of this stream of literature. Using this framework several aspects of IS and EIP structuration, functioning and evolution have been studied. Conceptual frameworks have been developed to consider and measure the influence of social and other factors in IS development. Baas and Boons (2004) developed an analytical framework to investigate the I.E projects life-cycle. They decompose initiatives in 3 main phases as "Regional efficiency" generating "Regional learning" implying "Sustainable industrial districts". Those phases being characterized by 3 objects, the creation of "collective competitive goods" (that is eco-efficient product of practices by actors), the "governnace mechanism" (the way actors are coordinated towards the recognition and creation of the good) and the "learning process of the system" by which we go from a phase to another. This perspective is used to analyze the I.E initiative (INES Project) in Rotterdam (Baas and

Huisingh, 2008). At this time the authors concluded that the system is still locked in the first phase.

On the basis of an extensive literature review, Boons et al. (2011) proposed a framework to analyze the IS deployment process dynamics through "institutional capacity building" (systems of practices allowing for the coordination of self interested actors towards a common objective) and IS concept diffusion in the society. They identify a set of "antecedents" (the business and political characteristics in an area) inducing "outcomes" in the ecological and social systems through "mechanisms" at the social level and the "regional industrial system" level. At the social level the authors retained the following mechanisms: "coercion" , "imitation", "government interest" , "training and professionalization" and "demonstration projects". At the regional industrial system level the mechanism at work which is considered is precisely "institutional capacity building". This framework is further used to investigate the EIP development in Terneusen (Spekkink, 2013).

Domenech and Davies (2011) developed a formal model to account for the impact of embeddedness in IS. Following the authors, embeddedness is a characteristic of relational networks in which "trust" , "fine grained information transfer" and "joint problem solving" frame a cooperative environment for business transactions.

Social embeddedness concept is mobilized to evaluate the "mental distance" between actors within an EIP and the influence it has on outcomes. Ashton (2008) proposed a framework and case study to assess the impact of social aspects in the final outcomes of IS in Nanjangund (India). Their findings indicated that no correlation was observed between communication patterns between managers and the implemented exchanges.

Branson (2016) re-investigate the Kalundborg EIP using "mental distance"

concept and found that such proximity is not necessary to achieve synergistic by-product exchanges.

Yap and Devlin (2017) built a generic framework to analyze the factors driving the development of I.S focusing on the behavior of firms towards IS which is affected by 3 "contextual factors" that are "market forces", "the state" and "civil society". While not statistically conclusive about the extent to which social ties do affect the actual realization of exchanges within EIPs, those sociological approaches explicitly considered actors as complex objects themselves and give keys to analyse their relationship as object of study, that is arguably of first importance in the study of IS.

Complex systems approaches

Social network analysis (SNA)

A formalization of social ties in EIPs is developed in contributions from Social Network Analysis methods.

A social network model is composed of nodes and edges (a graph) the former representing an agent and the latter a link between two agents. Using concepts of network analysis inherited from the mathematical theory of graphs, industrial symbiosis networks properties can be analyzed to give insights on the structuration of linkages. Ashton (2008) used this methodology to analyze the social ties patterns in the Barceloneta EIP in Puerto-Rico. A review of applicable indexes and network metrics for IS analysis is available in this work (Fig 1.5). The author assessed the link between social ties in the EIP (described from plants managers interviews) with the outcomes in terms of exchanges. IS have been found to be correlated with "trust" among managers but not with standard supply chain links.

A case study of the Kalundborg IS network structure has been proposed in

<i>Social network term</i>	<i>Description</i>	<i>Examples in this study</i>
<i>Node</i>	An actor in the network	Firms, managers
<i>Tie</i>	A relationship between a pair of nodes. Actors may share several different ties. A tie can be direct or indirect via another actor, quantified, and directional.	Among firms—selling or purchasing goods Among managers—trust A→B or A↔B
<i>Degree</i>	Number of direct ties for a given node	Number of firms to which the respondent sells goods
<i>Dyad</i>	A pair of nodes with a direct tie	A pair of firms exchanging by-products
<i>Geodesic distance</i>	Shortest path length or number of ties between two nodes	Distance equals 1 for two firms that have a direct tie
<i>Nodal average</i>	Average degree for all nodes in the network	Average number of firms to which respondents sell goods
<i>Density</i>	Ratio of number of existing ties to all possible ties in a network	Ratio of existing sales ties to all possible ties
<i>Actor centrality</i>	Measurement of how central a node is in a network	The firm that sells goods to the most others will be most central for this tie
<i>Network centralization</i>	Measurement of the degree to which ties are concentrated around a few nodes or spread out among many	A network is highly centralized if the majority of ties are with a few actors
<i>Ego-network</i>	The network of nodes and ties centered on a given node. Each node in a network has its own ego-network made up of itself, the nodes to which it is directly tied, and the ties between those nodes.	Firm X and all those to whom it sells goods, and their sales with each other
<i>Whole network</i>	All the nodes in a defined population and all the ties between them	The entire industrial ecosystem
<i>Star network</i>	A network configuration in which all ties are centered on a single node	The sole provider of a good or service is directly tied to its customers, who are not connected to each other
<i>Fully connected network</i>	A network configuration in which every node has a direct tie to every other node	All members of an organization have direct ties to each other

Figure 1.5: Social network modelling (from Ashton,2008)

Domenech and Davies (2011). The focus is descriptive rather than analytic. A set of metrics and indexes suited for EIPs modelling with SNA is proposed

in Zheng et al. (2012).

In another contribution following the latter, Zhang et al. (2013) proposes a set of indicators to analyze the structure of different EIPs and anticipate operational problems and the spillovers of failures within a IS network.

New network-based modelling practices are proposed as future extensions in Schiller et al. (2014) in order to cope with the multiplex aspect of industrial symbioses due to the co-existence of social and material ties within such networks.

Agent-based modelling

The consideration of EIP's individual actors have been modelled in contributions using Agent-based models. 6 references used such a modelling framework to adress the question of IS emergence. General introduction to such a modelling tool for IS are available in Batten (2009) and Bichraoui et al. (2013). A generic Agent-based framework tailored to EIP modelling is proposed in Romero and Ruiz (2014). In other contributions, more specific issues are investigated using such a methodology: Contracts between agents are included in Albino et al. (2016); Fraccascia et al. (2017) model the impact of landfill tax and subsidies in an agent based model of IS development.

Zhu and Ruth (2014) analyze the emergence of different network of exchanges coming from different growth patterns whose properties models various IS facilitators interventions.

Game theoretical models

Game theoretic microeconomic models formalize the interplay between each actors decisions. In that sense economics not focuses only on the impact of each actors decisions on each other payoff. The decisions are taken by actors

considering the decisions of others in a mutual way. Thus the controls (variables) mastered by one actor must parametrize the program which must be handled by another leading to compute equilibria instead of determining traditional optima. In many settings equilibria are then defined by conditions that can be analytically derived. The equilibria have efficiency properties regarding some modeller-defined measure of system value. Thus the economics approach of industrial symbioses must look at such efficiency properties of equilibria under a wide range of assumptions on the business context under study. Despite its interest only 2 contributions have been found so far in the literature on EIPs and IS. (Chew et al., 2009, 2011) proposed to ground the analysis of inter-plant water integration taking into account individual actors interests in the setting of such a practice. In the first model (2009) the interconnections are direct between plants while in the second model the network comprises a central hub to collect and dispatch the flows of waste water. Both non-cooperative and cooperative games approaches are investigated. Different network structures are tested and the Nash equilibrium is considered as the best solution for a subset of actors who exclude one participant whose participation in another network structure would have rather generated the best global outcome. The cooperative case corresponds in those contributions to the possibility to make binding agreements on cost sharing. In that case the first best can be implemented. In the second model (with central hub) the cooperative case consists in a green subsidy from a "EIP manager" who is interested in generating the first best outcome. It is shown (in the cases depicted in this article) that the green subsidy can restore the first best. We argue that those contributions could have used more generic instances and overall use the "coalition" concept to investigate the set of implementable network structures. Nevertheless the interest of this work is to enlight the

fact that individual choices must be taken into account when analyzing EIPs and that game theoretical analysis is a suited tool to address the question of IS deployment.

1.2.3 Eco-industrial parks developments: experiments, challenges and driving factors

Factors driving success or failure of IS

From a literature review of first contributions analysing experiences of EIP initiatives notably Heeres et al. (2004) and Pellenbarg (2002), Tudor et al. (2007) proposed a synthesis of factors affecting the deployment of industrial symbioses. A list of 18 factors are presented by the authors and includes political factors (Trust, cooperation, firms should not be competitors, privately driven initiatives, active participation from a range of different stakeholders), structural patterns (The presence of a large firm "anchoring" exchanges), organizational forms (monitoring of environmental performances, integration of environmental, ecological and spatial concepts, presence of an association of firms, information gathering), technical issues (diverse range of firms with complementary materials, sound financial planning, initial focus on utility sharing). Many drivers of different nature thus interact to foster or hinder the realization of exchanges and the adhesion to I.E principles.

Economic aspects nevertheless remain highly relevant drivers of IS implementation. In their study on the Devens I.E initiative, Veleva et al. (2015) do insist on the business aspect of IS and claim for a consideration of businesses needs to stimulate and anticipate I.E initiatives outcomes. In a recent contribution, Yedla and Park (2017) structured a comprehensive analysis of factors and strategies to foster the development of IS. Factors and conditions are clas-

sified as technological, social and regulatory and measures are proposed at different levels and for different actors. key "technological issues" raised are appropriate benefits sharing³, quality control and pollution limitation. On the social dimension, "multiparty coordination; the establishment of communication channel and trust creation among various participating actors" are considered as essential to the deployment of IS. Important "Regulatory issues" includes in turn "rules of hazardous waste management" adaptation to not hinder or cancel opportunities of resource substitution. A set of measures is then proposed so as to create appropriate conditions for successful IS development. At the societal level, green consumerism, eco-efficiency promotion and the identification of benefits of IS on climate warming are considered as key drivers. At a (political) national level many measures are proposed and are related to environmental regulations, the creation of "communication channels" between industry clusters and sectors and the promotion of I.E principles so as to institutionalize it. Park level measures could include the creation of coordinating structures to handle issues related to resources scarcity, multilateral arrangements setting and provide material flows analysis. At a firm level negotiate regulations on waste handling to allow substitution resource use is a proposed way of action and at a city level it is proposed to "Enhance marketability of "green products" for optimal resources utilization" and adopt I.E principles to manage municipal waste as a resource. From this literature study we thus acknowledge that factors driving IS are multi dimensional in nature, interacting with each other and can be influenced by different set of actors at several levels.

³According to our view "benefits sharing" pertains more to the economic nature of the transaction and we propose extensive, in depth analysis of this key issue in our work

Focus: Policy interventions and instruments

Industrial ecology cannot be separated from its institutional and socio-economic context so that one must pay attention to public actors contributions and interventions. In addition to its role as a participating actor being a source (municipal waste) and/or a sink (district heating) or even a processor (Korhonen, 2001b) local authorities can act as a symbioses enabler by shaping part of the eco-industrial park context through policies (Jiao and Boons, 2014). Consistent and pro-active land use authorizations and permitting have not to be a limiting factor to eco-industrial developments (Roberts, 2004). Collaboration stimulation through industrial ecology committees, project management support and infrastructure financing are the main supporting roles of public authorities to foster industrial symbioses (Paquin et al., 2015; Tudor et al., 2007). At a national or supra-national level, public authorities can influence symbioses environment through regulations and policies on pollution reduction objectives, waste handling and treatment regulations (Costa and Ferrão, 2010), disposal rules, CO₂ emissions, disposal taxes (penalties). Energy efficiency gains objectives can provide adequate incentives (Lehtoranta et al., 2011). The ease to access electricity market (Colmenar-Santos et al., 2015) is a key factor for some technological developments such as CHP plant development. Public interventions towards IS thus differ in their nature and play an important role in the implementation of synergies.

1.3 Synthesis and recommendations

Techno-economic descriptions of archetypal synergies are necessary to precise the evaluation and analysis of configurations achievable when designing a solution. Moreover, the taxonomy of practices we proposed helps to identify

the most auspicious candidates for IS (different flows and installations).

A complementary perspective is a socio-economic one in which actors roles and interaction processes are envisaged in a comprehensive manner. Following this institutional capacity building, trust, knowledge sharing and learning over practices as well as activities profiles, technical requirements or quality of by-products are key dimensions with strong impact on IS evolution. Some of those internal behavioral or governance assets may require time and proximity (humans workers with multiple multiplex contacts) but some needs IS launching (quality discovery, fine grained planning policies setting, technological properties and know-how) that explains differences in learning and spillovers depending on the density and depth of collaborations since on-paper project analysis (design phase) is usefull both for soft skills building and "hard" data and information gathering but it is somehow limited or different from insights and skills acquired during concrete IS operation. Another key element to understand why businesses may engage in IS is the symmetry of statuses since in some cases the exchange at the root of symbiosis is seen as an innovation for each participant, in other cases the supplier/provider (resp.the buyer/user) can be comfortable with the deal since it already master those type of resources and form of transactions (municipality using industrial boiler to incinerate part of its wastes). In order to stimulate the development of IS, public authorities then must target the funding of assets whose properties are conductive to IS. We identified the usual suspects with respect to this idea so that we advocate the use of Project financing schemes (for assets or overhead expenses) which is suitable if local authority can sustain in depth implication in the projects notably on large incinerators, CHP plants and waste water treatment plants. In case the public actor is not a direct stakeholder regarding the infrastructure use, subsidies can play a

facilitating role regarding investments in IS-compatible private installations.

Regarding the substitution synergies we recommend to pay attention to the legal status of wastes and the regulations of their transport or storage because it can play a key role. Those policies indeed influences the determination of the set of competent service providers (treatment and logistics) since some key competencies or legal authorizations (French law on waste status inducing transportation, handling and storage constraints) must be necessary to manage wastes. This set of constraints may discard resource substitution synergies because it is not allowed to exchange such items.

As a consequence, in line with the process representation we proposed, regulations striving for IS implementation should be thought as a system.

First, regulator should provide the right set of incentives and/or constraints to actors (fresh water withdrawals and pollution limitation, landfill tax increases), second, it should allow the substitution resource use by changing the items qualification as "wastes" (or limit the operational implications of such a classification).

A third and complementary set of measures is to sustain the diffusion of I.E "thinking" towards the society (communication, labelling of EIPs and educational training) and launch initiatives in which a (team of) publicly funded managers act as facilitators following the "Korean" model in which in depth project management can be undertaken so as to share the cost and train the manager to cope with IS specific challenges.

Public actors implication is then an important factor of success for IS but the original ambition of industrial ecologists for top-down, detailed and coercive planning should be amended.

Chapter 2

Perspectives on Industrial Symbioses: Case study-the Green Valley eco-industrial park

2.1 Case study description

In Chapter 1 we selected and reviewed 25 cases of eco-industrial parks that is parks in which industrial symbioses are or have been in function. Following the stream of literature dealing with EIP case studies, we propose in this chapter the analysis of the Green Valley eco-industrial park. Green Valley is an EIP located in the East of France in the Lorraine region. In this EIP several actors among which a huge pulp and paper mill (Norske Skog Golbey) do participate in industrial symbioses for more than 15 years. Our work thus complement actual developments about industrial symbioses worldwide with a new case study in the French pulp and paper industry (Molinier and LeNet, 2018). Chapter 1 investigations towards case studies on industrial symbioses revealed that the pulp and paper industry is a field for synergistic practices.

Excluding Green Valley, among the 25 cases, 3 are related to the downstream forest sector (Kaisersbaracke in Belgium, Kymi, Jyvaskla and Uhimaharju in Finland). By doing such a case study, our aim is first descriptive since we make available a new case study and thus propose an additional object of study for industrial ecology researchers or practitioners. Second we aim at understanding the structuration and the influences that triggered and maintained the processes by which the symbioses emerged. Third we used this case study as a learning instrument regarding new or additional important dimensions to consider in IS research and also in the learning of microeconomic aspects of such projects especially contracting process (see Chapter 3) to structure our reflexions on applicable models with insights from the field. As a result we propose a new test of literature indications that we use as a framework to analyse this EIP. Moreover we also complement and extend literature lessons with the processes, informations and elements drawn from the case study. In a first part, we set up our analytical framework, research questions and units of analysis. In a second, we describe the actors, processes, context and informations of the case study. The third part describes chronologically the sequence of events that constitute the Green Valley EIP lifecycle and we then propose a perspective on the processes at work using theoretical frameworks and we characterise this particular EIP with elements from the literature.

2.2 General approach and research questions

Units of analysis: analysis scope through an I.S framework

To analyse this case of eco-industrial park we describe and put in perspective all the relevant aspects of favourable and detrimental factors and explain the process by which symbioses emerged. To do so we should target the elementary pieces that structure the system under investigation. First we set the boundaries, we consider and give a description of the appropriate contextual informations relevant for the analysis of the symbioses at stake. To do so we look at the set of actors involved in the symbioses and their respective roles in the IS deployment process considering their resources, objectives and relational ties with others.

More precisely we investigate which are the symbioses dynamics mode at work in the Green Valley symbioses insisting on the influences of various economic, organisational, regulatory, social and technical factors on the development of the various symbioses at work or in project in the Green Valley EIP. For this we use the concepts proposed in the litterature regarding industrial symbiosis dynamics (Boons et al., 2017) in order to characterize the way the Green Valley EIP has developped notably with the Anchoring process (Sun et al., 2017). IS exhibits path dependance property (Boons and Baas, 1997) meaning that deployments are not neutral from the historical envents preceding the implementation of a particular asset use or flow transfer (see 1.2.1). The nature of resources and assets used in IS evolve with time from simple (order pooling, utility sharing) to complex objects (co-innovation for conversion). The territorial scales and their relationships in IS will also be looked at as a key element notably through industrial sectoral and regulatory/policy impacts on IS deployment (Yap and Devlin, 2017). In addition

we shed light on the organisational forms (see Chapter 3) actually used in the various symbioses in the EIP .

Methodology and data collection

To go in-depth in this case study we first set up an agreement with the EIP main actor, the NSG pulp and paper mill (with a confidentiality agreement). Following this we had access to a wide set of informations and resources to investigate in details the IS. Access to confidential data (for this reason not displayed in this work) was helpfull to gain in-depth understanding of the case. Among those private data included access to contracts, material and energy quantities, projects prospective business plans, equipments' bill-of-specifications, detailed process flowcharts.

We also had a detailed visit of the production plant from paper production lines, materials handling systems, gas boilers and CHP plant as well as the wood handling platform. We also conducted semi-structured and informal interviews with stakeholders especially NSG staff including the plant director, energy managers, project managers and teams. Interview of EcoDev coordination body has also been conducted.

In addition we used publicly available data sources on the companies or on the projects within the EIP. Those resources were issued from institutional reports (Oree, Ademe), NSG Results publications (environmental and financial statements) and local or technical press (L'usine nouvelle, Vosges matin, Actu environnement).

As a result we represent the relationship using a graphical representations with diagrams with edges and arrows for ties and boxes for entities. Detailed information is provided on the diagrams when necessary.

We investigated what are the Green Valley patterns and whether or not it

fits with literature findings regarding the question of deployment dynamics, synergies implemented, their driving factors and the organizational structures used.

2.3 Analysis

2.3.1 Territorial context

The Green Valley EIP is located in France in Golbey, department of Vosges, a little locality close to the city of Epinal in the Lorraine Region. The urban area population is around 111 000 in 2018. This territory is endowed with important forests. Wood is the main local natural resource. Regarding the industrial site of Golbey, wood and waste paper sourcing is mainly sourced from France but also from other European countries. Main economic and technical regulations that apply are thus French law and policies. Strategic sectoral influences are nevertheless international because related to the paper industry whose market is highly internationalized and the pulp and paper mill is part of a Norwegian group. Newsprint is indeed the main final product of the core actor of the EIP the Norske Skog Golbey pulp and paper mill.

2.3.2 Sectoral context

The central actor of the EIP is a Pulp and Paper mill (Norske Skog Golbey).

Its average sourcing radius is 140km for wood and (95 %) is harvested in France (the remaining is imported from Belgium and Germany). The site processes around 235000 tons of wood a year for newsprint production and

consumes around 115.000 tons of wood by year for energy purposes. The second input material which is used to produce paper is waste paper. This second hand resource is issued at 90 % from France and 10 % from other European countries (Germany, Switzerland and Belgium). The annual use of waste paper is around 500.000 tons.

Globally the publication paper market segment (newsprint) of the Golbey site experienced a decay of activity because of dematerialization and a shift of production from Western Europe to Eastern countries making the situation of such companies very difficult. Golbey is the last pulp and paper mill in the northern France. Nevertheless NSG is still the first Pulp and Paper mill for newsprint in terms of production capacity in Western Europe (600.000 tons per year).

2.3.3 Actors at stake: resources and objectives

Here we define actors their status and roles (resources, capabilities, decisions). We investigate in depth mutual linkages in the subsequent parts about social ties and organizational aspects.

EIP industrial actors

- **Norske Skog Group (Company):**

As stated above NSG is a production site of the Norwegian company NorskeSkog. This firm was created in 1962 by a group of Norwegian forest owners and developed during the 70's and the 80's in Norway where it took the leadership of the paper production sector. In the late 80's and 90's NorskeSkog grew abroad and invested in production site outside Norway (the first site being the french site, NSG). At the end of the 90 decade the company invested in other firms taking part in joint ventures worldwide and became a world

leader in the paper industry. Due to the decline of newsprint demand in the 2000's disinvestment occurred in order to concentrate on the European market and historical production sites with the strategy of switching the global revenue model radically with the ambition of generating 25% of the company revenue in new activities and notably the production of bio-energy and innovative bio-materials.

- Norske Skog Golbey (Business Unit):

As we will detail further, the Green Valley EIP is centered around the activities and projects of a core company, the Norske Skog Golbey pulp and paper mill (NSG). NSG is the first production site of the Norwegian company NorskeSkog (see below) built away from Norway. From the beginning of its exploitation in 1992 the production capacity expanded with the setting of a second production line on site in 1999. In 2017 the cumulated investments in the Golbey site is around 830 millions of euros. Regarding workforce, 325 employees run the mill whose gross revenue in 2017 was approximately 300 millions euros.

NSG core processes for paper production is organized as follows. First it is a thermo-mechanic process comprising 2 production lines of 600000 tons per year global capacity. Those two lines uses waste paper and wood as inputs with shares of 60% and 40% respectively to produce fiber which is melted with water to obtain pulp. Water sourcing is one of the other major inputs used to product pulp with an approximative ratio of 70 m^3 of water for 1 ton of final product (paper). This important use in volume is nevertheless limited by a high recirculation rate of 85 %. Regarding water use, 2 % is evaporated and the remaining 13 % is being returned to the source river (the Moselle) after treatment in the site's Waste Water Treatment Plant (WWTP).

NSG auxiliary processes for utilities (steam) production is ensured by a

fluidized-bed boiler whose capacity is 100 MW since 1999. Formerly when the production consisted in only 1 paper production line steam supply was performed by a gas boiler of 20 MW capacity. Back-up supply system consists of 5 gas boilers with capacities ranging from 12.5 to 31 MW. Globally primary energy for heat supply is produced with wood (60 %), processes waste (30 %), gas (10 %). Electrical power consumption is high with annual quantity of 1 TWh. Half is induced by the pulp production process.

NSG biogas production plant uses an aerobic treatment of sludges from the site Waste Water Treatment Plant. Oxygen and bacteria treat those in a first step. In a second step an anaerobic process (within a digester reactor) converts the organic products from the aerobic reaction in biogas. Then this gas has to be purified resulting in the production of biomethane and CO_2 .

- Pavatex:

Pavatex is a Swiss company producing thermal insulation panels for wooden framework houses. Among its 3 production sites, one is located in Golbey, on the NSG owned site. This 60 millions euros plant has a annual production capacity of 50.000 tons of panels. Pavatex produces insulation panels for composite wood construction. Its processes mainly involve use of wood chips and heat for the drying and consolidation processes. 2 types of steam are used for production. 2.8 bars from surplus steam generated by NSG processes for the heating of chips and a 24 bars steam for drying purposes. The steam transfer from NSG represent 2/3 of thermal needs at Pavatex factory. A 6 bars steam is produced by mixing the 2.8 and 24 bars with an innovative process. This mixed steam is used for wood chips cooking.

- Nr Gaia:

Bio-based Insulation producer NrGaia had set up a production plant (with a capacity of 30.000 tons per year) within the NSG site in 2009. Highly

financially sustained by local public authorities (Epinal-Golbey municipality council) and NSG got 16 % of NrGaia's shares. There were great perspectives but shifts in sectoral specifications about materials drawn down the company activities. Bankrupt in 2014.

- Arbiom:

Biotechnology company specializing in biomass conversion into inputs for nutrients, biofuels and chemical products. Arbiom has a research center in France (Evry) and in the US (Research triangle park, North Carolina). Moreover it also operates a pilot plant at Norton (Virginia) and had set-up a demonstrator near to NSG mill.

- Elyo (Suez):

This utilities company is specialized in the management and maintenance of decentralized energy production systems like biomass power plants or combined heat and power (CHP) plants.

- Eurorail:

Logistics service provider (including rail) final product expeditions and material import on site.

- Michelin factory and 2 other industrial sites:

Additional industrial actors are associated to the long term project of valuing the residual heat and steam supply capacity in the former gas fired boiler whose operation have been stopped in 1999. 3 industrial actors are under prospection to have access to the prospective heat supply among which we only have information on Michelin.

EIP public/institutional actors

- Epinal-Golbey municipality council:

Local public authority involved in the economic development of the Epinal

locality through local actors coordination, funding and local land use authorization policies.

Coordination bodies:

- EcoDev:

In order to maintain and develop industrial activities in the Epinal locality the Epinal-Golbey municipality council and NorskeSkog Golbey founded an organism "EcoDev" to sustain projects, initiatives and implantations of potential business partners.

- CRITT-Bois:

A technical and expertise center located in Epinal in charge of coordination industrial actors and research institutions as well as innovation projects support in local well implanted sector of and eco-friendly material for building.

2.4 Results and discussions

2.4.1 Sequence of events (chronological development)

Step 0-Industrial activity initiation:

The initiation of the industrial activity in the Golbey site has been launched with the set up of NSG's pulp and paper mill in 1989. One pulp production equipment (using 70 % of pulp chips and 30 % of roundwood) was associated with one paper production line. A 20 MW gas boiler supplies process steam.

Step 1-NSG's Energy mix shift:

A shift in NSG energy production processes occurred in 1999 when a second production line had been set up. It resulted in increase in capacity (600000

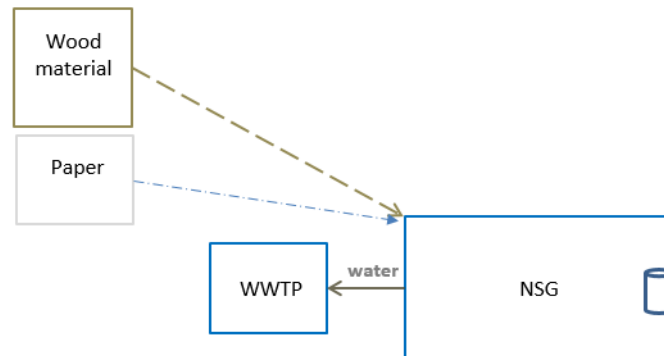


Figure 2.1: Pulp and paper mill initial configuration

t/y) and so in the energy consumption. As a consequence managers decided to opt for a new source of energy to keep competitive and discarded the first gas boiler for steam production by installing a 108 MW fluidized-bed boiler incinerator. Such a technology enables to feed the boiler with a variable mix of primary energy sources especially biomass and various industrial wastes. NSG energy mix for steam production thus shifted from gas to waste wood products sourced externally and internally reused industrial wastes (barks, residues...). The mix of wastes used in the new boiler is then related to NSG core processes. This mix is composed of 60 % of waste wood, 22% of sewage sludges, 6 % of pulping process waste, 2 % of waste paper and plastics. The remaining 10 % are issued from gas consumption. At this point the "symbiosis" is both based on internal use of wastes and on the use of regional external sources for steam supply (waste wood).

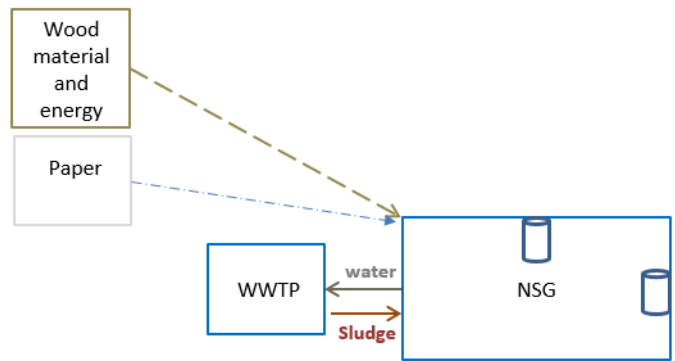


Figure 2.2: Fluidized bed boiler installation

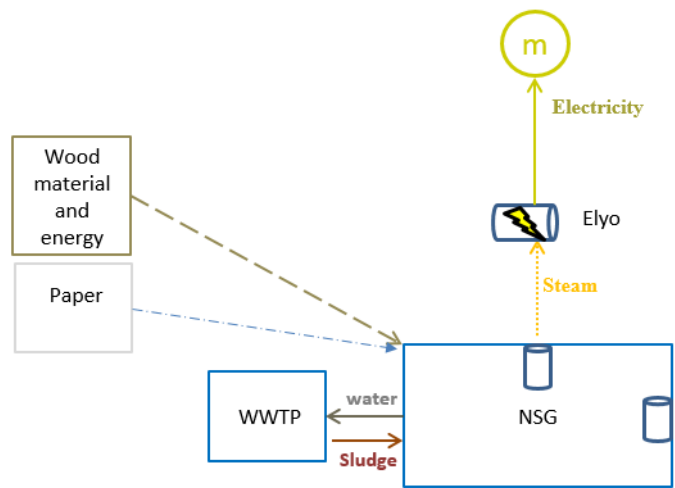


Figure 2.3: Cogeneration turbine installation

Step 2-Cogeneration turbine installation:

In 2009 following a National call for decentralized electric production projects through cogeneration (supervised by the CRE) NSG signed up a partnership with Elyo (Suez) to install and operate a 12,5 MW cogeneration turbine by

fitting its fluidized-bed boiler.

The resulting annual electricity production ranges between 68 and 72 MWh. NSG benefits from this partnership through the sales of process steam to Elyo which in turn feeds electricity (produced by the turbine) into the national grid after having sold the electricity to Edf, the national electricity producer. This additional revenue source for NSG is associated with a set of national policies related with energy mix transition objectives. In order to obtain the final authorization for electricity supply many steps and requirements have to be completed. Capacity choice is indeed constrained by the CRE tender which ensures global consistency regarding policy objectives and equipment installation and operation is constrained by national regulations on environmental risks mitigation (ICPE regulations). Economic constraints issued from a complementary set of regulations consist of the way electricity finally feed into the national grid is paid to the producer. In 2009 the mechanism consisted of a fixed guaranteed feed-in-tarif (FIT). In this symbiosis NSG is then the primary energy supplier (steam) while Elyo is a technical partner whose role is to convert the steam into electricity for injection into the grid. Then Edf is the actual downstream client.

Step 3-The NrGaia synergy:

In 2009 the producer of bio-based insulation materials NrGaia enters the NorskeSkog Golbey industrial district and installed there a facility with a capacity of 30.000 t per year. This innovative firm whose core process was engineered in the ENSTIB laboratories firm was settled after having received strong support by the CRITT-Bois and the deputy-mayor of Epinal who engaged funds from the Golbey-Epinal municipality to scale-up the process. To sustain the installation on its site and gain access to strategic information

Norske Skog invested in NrGaia and got 16 % of its shares. In terms of eco-industrial synergies, NrGaia benefited from a business estate leased to NSG (on its own site) and leveraged NSG bargaining position on the waste paper market to obtain price rebates. This synergy operated during 5 years until NrGaia went bankrupted in 2014 because of a shift in sectoral material standards evolution and critical default by one of its key input suppliers.

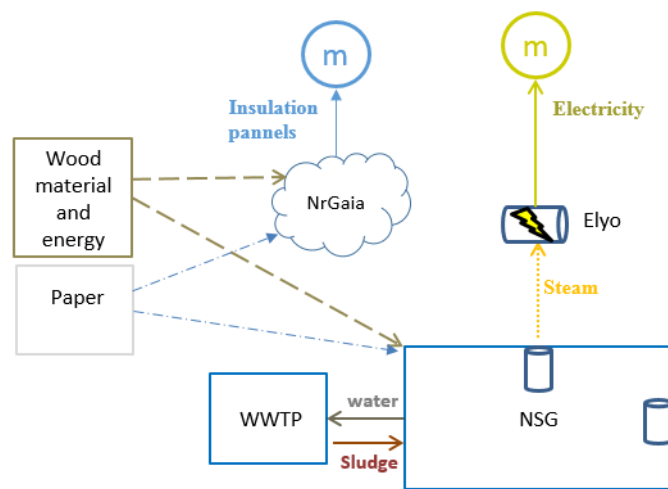


Figure 2.4: Pooling synergies with NrGaia

Step 4 - Green Valley cluster labelling:

In order to gain visibility, the municipality and enterprises of the EIP labelled their joint eco-industrial initiative as "Green Valley" in 2010 to institutionalize the EIP (for internal and external communication and coordination). Green Valley will receive in 2014 a circular economy prize from the French ministry of environment for its achievements (Figure 2.4).

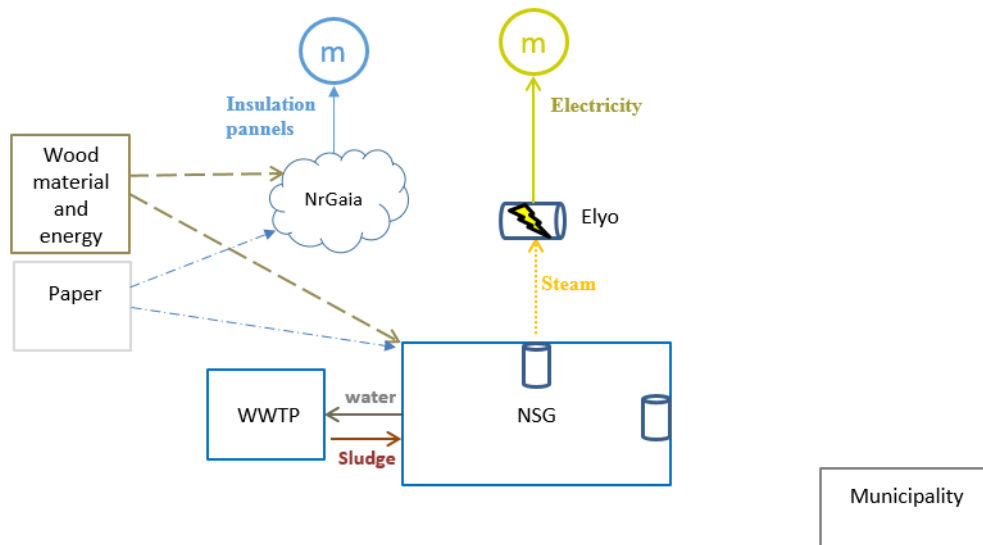


Figure 2.5: Cluster labelling and prize

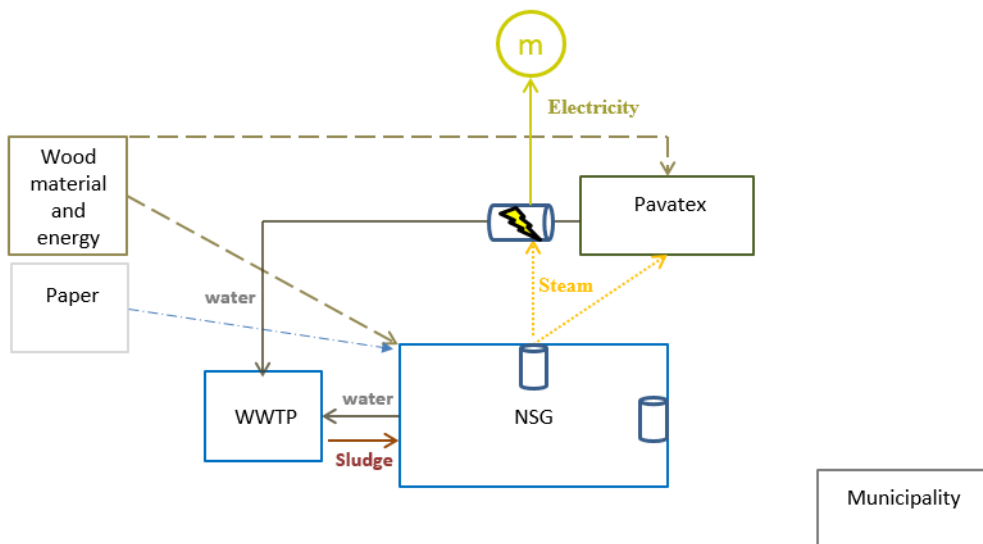


Figure 2.6: Entry and Exit

Step 5 - The Pavatex synergies and the exit of NrGaia:

In 2013 Pavatex entry in the Green Valley and installation within NSG industrial estate enhanced further the synergies in function in the EIP. Indeed both substitution and infrastructure/service sharing synergies have been developed. First in the same way it happened with NrGaia for the sourcing of waste paper, NSG and Pavatex pooled their demand orders so as to obtain rebates on wood prices (especially for Pavatex) and achieve better use of the site's wood handling platform (2 users sharing the costs instead of 1). In addition Pavatex gained access to the waste water treatment plant of NSG thus avoiding the build-up of its own leading to gains on capital expenditures. Regarding resource substitution synergies, Pavatex sources 2/3 of its global steam requirements from the use of NSG processes excess heat. In 2014 after financial issues due to external factors and industrial concerns NrGaia went bankrupt and exit the eco industrial park.

Step 6 - Biogas production:

In 2017 a 17.000 MWh/year capacity biogas production plant has been set-up in the industrial estate by NSG. The corresponding investment of 7.1 M euros have been financed partly by the ADEME (1.6 M euros participation). This investment has been motivated by the diversification strategy of NSG and stimulated by guaranteed feed-in-tarifs (on long term contracts and indexation) by the French gas network operator. This production unit uses the waste water treatment plant sludges to produce biogas. The upstream inputs are then supplied by NSG and Pavatex core processes. A second unit is under evaluation and could produce biogas from organic waste sourced from the municipality (Figure 2.7).

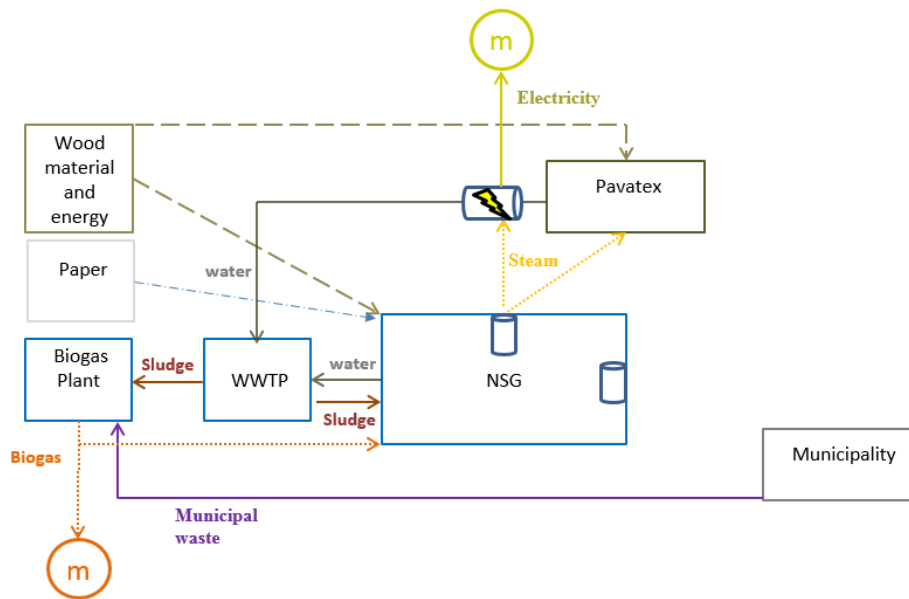


Figure 2.7: Biogas supply

Step 7 - Biorefinery:

NSG and Arbiom launched a partnership to settle a biorefinery demonstrator on NSG site. The total investment amounts to 40 M euros and is financed in part by a 10.9 M euros from the European Union which is associated to the Sylfeed project. The idea being to convert (low value) lignocellulosic materials (wood residues) into valuable proteins for fish alimentation. The Arbiom biorefinery process would (in a first phase) use 5.000 tons a year of lignocellulose from NSG (non-contaminated) waste wood to produce proteins and other chemical co-products. The expected industrial scale-up would result in the settlement of a biorefinery whose installation would take place in an available land owned by NSG close to the actual site.

Moreover this unit is planned to use heat and steam provided by the shared infrastructure at stake in the "Energy Island" project (step 8).

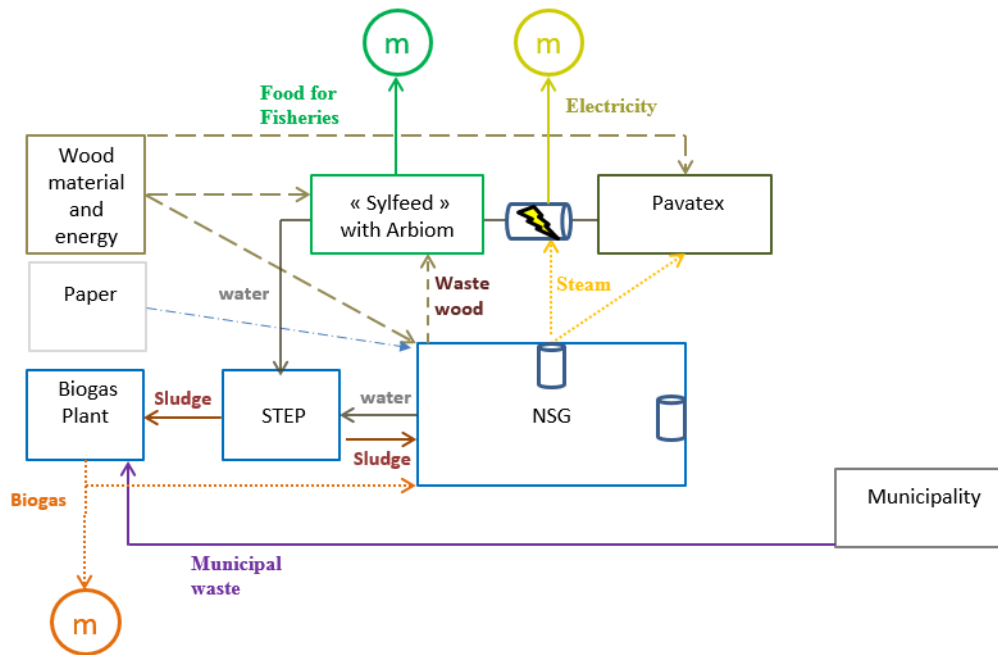


Figure 2.8: Biorefinery

Step 8 - Energy supply: Energy Island project

Project "Energy Island" structured around a collective vehicle called "Green Valley Energy" seeking both infrastructure sharing synergy and substitution synergy. The project consists in retrofitting the former gas boiler which is unused since 1999 to fuel it with biomass and waste to generate steam. 3 industrial actors have been targeted as potential users of steam (among which a Michelin factory). The municipality is also interested in supplying part of its district heating network using this boiler. The Arbiom's expected industrial-scale biorefinery would also be supplied by this asset. For this last case we must indicate that this service is bundled with access to a land for plant erection thus easing both installation and exploitation (Figure 2.9).

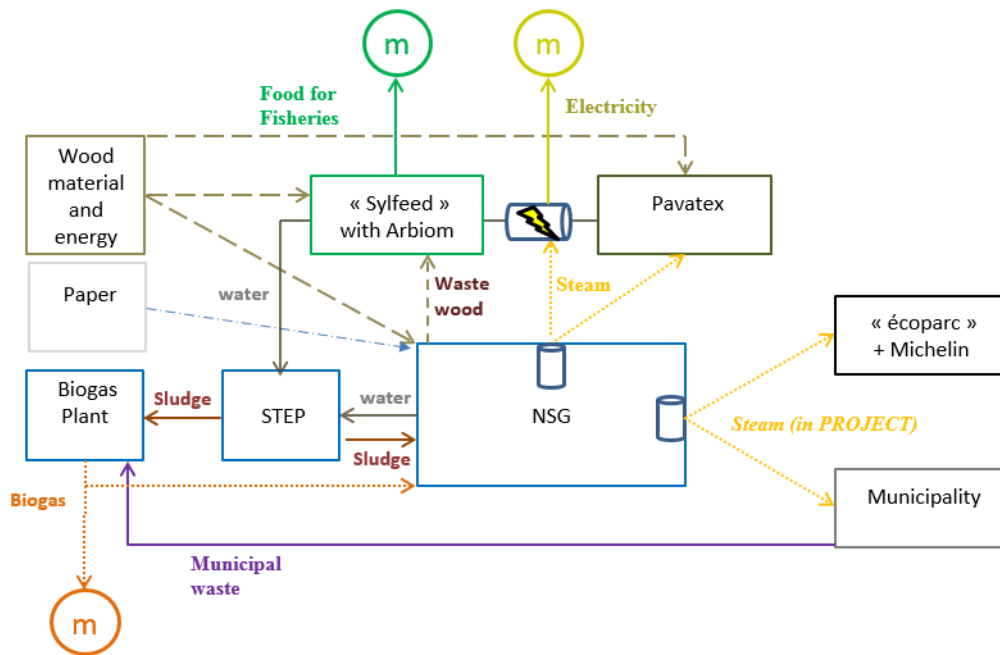


Figure 2.9: Energy Island project

Step 9 - Further Projects based on innovation:

2 other projects under consideration at the Green Valley involve partners in different fields. The first (NorFill project) aims at producing plastics and concrete materials from boiler ashes. Success would imply to replace costly treatment of ashes by earnings from corresponding sales (substitution synergy). The second one targets high value conversion of wastes through the use of wood embedded components for pharmaceutical products ("Le Bois Sante"). Unlike the existing symbiosis projects requiring organisation, investments or scale-up validation, those last projects still need R&D effort to be closer to completion (Figure 2.10).

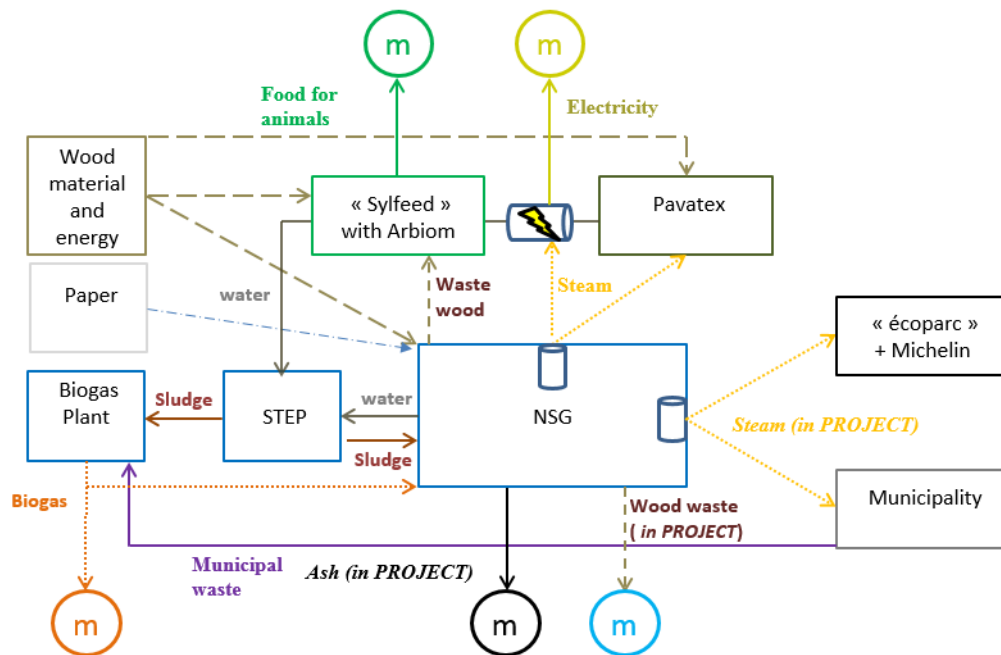


Figure 2.10: Further projects

2.4.2 Social ties

Social links have been shown to play an important role in the deployment of IS. Regarding this aspect the high importance of NSG activities on the territory (employment and wood suppliers networks) induce strong ties with many public institutions as municipalities, technical center for wood industries (CRITT, FCBA¹) and higher education engineering school specialized in the wood related industries (ENSTIB). Moreover during interviews we have been acknowledged that the initial fundings for NrGaia set-up were issued from a meeting between the deputy of Vosges met the manager of the CRITT supporting also the project of developing the local area on 2 historical sectors (Image technologies and Wood).

¹French Institute of Technology for Forest-based and Furniture Sectors

2.4.3 Organisational structures

Individual actors involved are of two types: Private actors, national public authorities, local public stakeholders, coordination structures. The key aspect with the Green Valley EIP belongs in the interplay between national level regulatory frameworks, industrial governance structure shift of Norske Skog pulp and paper mill to a business unit and the other several Business-to-Business relationships (B2B).

Internal re-organization of Norske Skog resulted in higher strategic autonomy for NSG and thus redefines the way decision making operates regarding the main actor of the EIP that is the NSG pulp and paper mill. This organisational shift changed investment decision process and as a consequence allowed local strategy definition. Attitudes towards industrial symbiosis has been reinforced. In between industrial actors within the park long term contractual arrangements have been carefully designed especially between Pavatex and NSG (steam supply). Pavatex and NSG use long term contracts with financial participation of NSG to Pavatex capital (minor thus not constituting a joint venture) in order to get in-depth strategic information but not strategic decision making over Pavatex assets. In the case of the cogeneration synergy, without getting into fine grained technical details due to privacy issues the cogeneration injection on the national grid is based on a contracts continuum in between NSG and Elyo (Suez) and Elyo and EDF. EDF's role in the contracting process is quite limited since conditions are fixed by the law. Contracting activity is mainly between NSG and Elyo to ensure mutual profitability in the conversion of NSG's steam flows into electricity. Interpenetration of those contracts downstream is fixed by law and

quite standardized (few room for private negotiation, arrangements). On the reverse the contract between industrial actors exhibit a complex structure and is negotiated since it directly deals with the heat supply constraints associated with eco-industrial risks (see Chapter 1).

Relationships with external industrial actors can differ. Regarding equipment manufacturers, once signed purchasing and maintenance contracts do not play a crucial role in the exploitation phase. It affects only the design phase of the relationship and the subsequent constraints on operations.

In the case of wood suppliers which are numerous and trade an homogenous good for the NSG and its partners in a given quality segment. Products delivered can be of heterogenous qualities but are managed with categories. NSG purchasing department is mainly contracting on price in a form close to market governance in between wood suppliers and the pool. Wood suppliers are managed with the purchasing pool which high bargaining power. The pool organisation itself is a coordination body driven by NSG since it is the biggest contributor, the powerful buyer within the pool and has the best knowledge of suppliers networks for both good quality process wood and poor quality wood for energy production. In fact it is NSG that negotiate with suppliers and manages its portfolio of suppliers and then sells the required amounts to its partners (within the pool) who then benefits from price discounts (win-win). Contracts are rather standardized and managed to obtain less prices with rolling renegotiation periods that can induce relationship disruption.

National authorities also interact with local industrial business through incentive schemes and various binding constraints (notably the ICPE rules on waste handling, combustion and plants pollution prevention). Author-

ity relationship is policies applicable to businesses. We will focus on such relationship in more details in the subsequent subsection.

2.4.4 Regulatory and policy aspects

As stated in the territorial context, at the higher level of system boundaries the activities considered are under French law and regulation policies. First of all, the use or generation of certain type of materials is limited or prohibited especially when it comes to incineration operations in industrial boilers. The link with contracts established in a B2B relationship between NSG or other industrial actors and their equipment manufacturers is induced by the elaboration of the bill of specifications that must comply with regulatory constraints in addition to business-related requirements. It gives additional design iterations in the global symbiosis projects definition since it shapes the technical constraints on the project and the costs increments induced by different resource-use configurations.

Environmental policies and coercive waste management constraints are thus at stake. Incentive-based regulations are salient in this case study. In France the gas and electricity distribution networks are owned and operated by national quasi-monopolies and strictly regulated to ensure market power limitation and renewables energy sources penetration into the mix. EDF, is the French main electricity supplier. Most of its capital is owned by the French state. EDF is not the owner nor manager of the electricity distribution network due to regulations applied in the early 90's that extracted those competencies from EDF's activities scope. This role is performed by another subsidiary company, RTE. considering biogas supply and markets the French gas distribution network management company (GRT Gaz) is the key stakeholder.

Following this both biogas and electricity injection in the network is subject to constraints to ensure consistent deployment of renewable decentralized sources of energy production (including biomass) in order to match decarbonization objectives that are in turn defined upstream by governmental guidelines.

All those stakeholders being regulated by the CRE (French Commission for Energy Regulation) which monitors and authorizes decentralized production like in the examples developed in the Green Valley EIP. It is in charge of the monitoring and control of the energy system evolutions in France after the dismantling of the National monopoly in the electricity sector formerly on the hands of EDF.

All those stakeholders do interact at different levels when it comes about supplying energy from decentralised units like the ones at stake in the EIPs. In our case study another important public actor the ADEME (French Environment and Energy Management Agency) plays a key role. Indeed this central state institution is responsible for sectoral studies, policy design, networking and project funding in relation with energy efficiency. Most importantly ADEME supported financially projects in Green Valley but is also participated indirectly to the various projects structuration since it requires in-depth multi dimensional descriptions of assets, resources, technologies and environmental benefits associated to industrial symbiosis projects for them to be evaluated before funding. To summarize national level regulations and policies do affect the dynamics of I.S in this EIP since it delineates resources use constraints, assets revenues (power and gas injection markets) and assets and project costs (funding, project structuration and equipments). It provides authoritative external conditions and fostering shocks/incentives affecting the deployment of resources and assets in the EIP, thus the imple-

mentation of synergies.

2.5 Synthesis and recommendations for eco-industrial parks analysis

IS in the Geen Valley: types of resources and assets involved

As a first step in the EIP structuration, internal reuse of waste occurred at the NSG facility when fluidize-bed boiler has been set. Chronologically the second synergy involving another actor were the estate sharing and order pooling practices between NSG and NrGaia. Those first cooperations involved almost no capital expenditures and only limited dependence (but substantial gains for NrGaia). The following set of synergies implemented with Pavatex were also "organisational" (order pooling for wood sourcing) but also process oriented with the sharing of NSG WWTP (requiring some investment in pipes) but overall the more complex steam transfer from NSG to Pavatex core processes (requiring investment in equipments). The nature still is about utilities exchange. The biogas plant erection then increased the complexity and investment requirements for NSG. The last projects complexity is higher since it supposes technological innovation, substantial investments and/or complex organisation setting (multilateral governance of the Energy Island project). To summarize Green Valley is emblematic to lessons issued from other EIP analysed in the literature since the nature and technical/organisational complexity of IS projects increases over time (service, estate sharing to utilities sharing/transfer, use of simple conversion processes, innovation and multi-sided pooling projects with important investments).

Industrial symbiosis dynamics in the Green Valley

Choices about resources uses, reallocation of capacities, flows and available land are dependant on only 1 actor's operations strategy (NSG) and its direct business partners. This EIP is in line with the "Self-organized" form of dynamics following the taxonomy established by Boons et al. (2017). Due to its position it is clear that "Anchoring" is the process by which this self organization operated even in the presence of a coordinating body whose role is more supportive than strategic. The coordination body ensures communication and facilitation notably about land use and pre-project support but not involved in contracting or operations. It is not responsible for the data handling and dissemination. Thus Green Valley is mainly self-organized but has been supported by a facilitator who have more the role of a "Broker" so that we can argue that Green Valley is an Hybridation of Self-organized EIP with partial recourse to a "Facilitation-Brokerage" type of governance punctually.

Territorial scales interrelationships

IS implementation in the Green Valley EIP have been influenced by national scale energy policies, local anchoring process around NSG business model shift (25 % of Gross Operating Earnings not generated from Paper core business, especially from Bioenergy supply). Integration of general firm worldwide sector policies and environment to re-organization and local rent-seeking interacts to sustain I.S. Influences on potentials with both national policies (climate change and national energy planning) and local development willing by municipalities and political staff.

Path dependance property

Strongly path dependant, many synergies occurred because former emerged. The key equipment in the Green Valley symbiosis is the fluidized-bed boiler (installed in 1999). Indeed it anchored many of the flows and capacity allocation since it freed the 20MW gas boiler for alternative uses (Energy Island project). This case of using a discarded capacity is original across other EIP reviewed, maybe because of a lack of in-depth information about such strategy in other cases. The capacity installed indeed allowed to pool the needs of many actors dynamically (boiler, land, industrial estate surface).

Factors influencing IS deployment

Global sectoral context and positioning of the anchor-tenant induced a shift in its business model in terms of targeted markets and internal organizational change. As a consequence of the business unit re-organization (decision and strategy decentralisation), industrial symbioses appeared as a value-adding activity and the organisational means required to investigate, evaluate and financially commit to their implementation became available to the pulp and paper mill. Regulatory conditions and national policies towards energy efficiency or climate change mitigation also had a strong impact on the implementation of IS. Some conditions and prohibitions reduced the scope of synergies while other added complexity in the bill of specification choices with equipments manufacturers. Even if such regulations can hinder the realisation of IS other stimulated further synergies (CHP plant) or gave them more value (biogas production from sludges pooled in the WWTP). Social ties at the local level can broaden the scope of synergistic projects like in the case of NrGaia entry in the EIP and switch incrementally the business content of discussions between stakeholders (from land use to supply steam

infrastructure sharing between industries and the municipality).

Organisational design and cooperation is another highly influential factor. The long term contracts does secure the necessary investments in conversion or transfer equipments required in IS. Contracting capability is in fact a key asset towards the design of win-win business relations. Depending on the relative competencies or effectiveness coordination can be achieved through monitored delegation (like in the purchasing pool) or detailed contract setting over results and warranties.

Chapter 3

Economic modelling of resource substitution synergies

3.1 Transactions, organization and economic governance: a literature review

3.1.1 Contracts in economic governance

The core of our research development is stated by Brullot et al. (2014) when she points out issues on the emergence of governance structures for eco-industrial parks : "...the analysis of coordination modes, one one hand, and the question of their endogeneity, on the other hand, are two of the main issues in the understanding of industrial and territorial ecology projects...".

Industrial symbioses strategies implementation in an eco-industrial park exhibits characteristics whose the influence on economic processes have to be taken into consideration for further analysis. Economics provides a set of approaches tailored to encompass these contextual properties in the analysis of the economic system behavior and status.

Commitment to an eco-industrial relationship is a critical issue in implementing industrial symbioses. Intensive capital investments in (site) specific assets dedicated to the eco-industrial relationship limits the willingness to participate in the eco-industrial park. Economic literature proposed solutions to solve or mitigate this reluctance. Long-term contracting and integration through ownership rights allocation among the partners are presented as well suited organizational devices to achieve mutual commitment.

On the operational side (unit costs and production rates) there can be uncertainties over the process efficiency and resource availability both in terms of quality and quantity. The same holds for the downstream requirements. Thus in a buyer-seller relationship it exists some risk exposure which can be asymmetric. Most of the models in the economics of contracts literature deals with such risk exposure by assuming a timing structure where some strategic decisions (contracting and investment) take place before the uncertainties are resolved. Exposure to relationship specific risks may contribute to commitment limitation as long as low outcomes are anticipated by at least one of the actors in a buyer-seller relationship. Opportunistic behavior may also arise after uncertainties resolution since this new information shapes a new business context (by redefining dependency balance).

The historical timing for symbioses implementation is of first importance since it defines the relevant set of economic conditions. The bargaining positions, assets ownership, control rights and contractual agreements define the economic problem faced by each actor at the time of analysis. The analysis of actual symbioses at work in eco-industrial parks has to carefully identify the timing of transactions implementations as it is informative on the market structure underlying the deals executions. What we observe is the result of a process which has been operated in a particular context. Long-term

commitments and specific investments might restrain the set of business and technological opportunities that can be handled. Budget limitation policies regarding investment at the corporate level or liquidity constraints at the business unit scale might also restrict the set of possible synergetic relationship to be implemented in a given time horizon leading to arbitration between projects despite the profitability of each opportunities.

The literature in economics is grounded on seminal works of Coase (1937) and Williamson (1979) who studied organizational forms of economic transactions as a response to specific interaction related issues giving birth to the *transaction cost* approach shaping the institutional economics stream.

Asset specificity is one of the key feature of industrial symbioses. Its influence has been widely studied in the context of bilateral buyer-seller relationship. The capital intensity of the required investments will lead to look at different financing schemes (project finance and its complex contractual structure can be used in case of large investments). The dependency is higher when assets are specific (that is have much higher value in a particular transaction than in any other) and this dependency is increased when the capital intensity is high. Dependency might also be asymmetric leading to commitment problems. Dependency asymmetry can induce opportunistic behavior if one actor is more dependant from its partner than the other is as long as the pending threat to leave the relationship is credible. In a buyer-seller relationship this behavioral issue is the so called "Hold-up" problem (Coase, 1937).

Hold-up arises when investment is set before entering the pricing negotiations. Once the supplier has invested in the specific assets to serve the client the latter has interest to claim for a price which is equal to the marginal cost. In that case the supplier must accept the offer and do not have any

way to induce the buyer to pay more since he can always switch for another supplier in the spot market (because of its independence). Conclusions from this simple example can be changed if we assume different market structures or a certain degree of dependence that cancel the credibility of switching. Several combinations might exist with different degrees of dependence asymmetry (Buvik and Reve, 2001). A set of literature justify the use of formal *contracts* among other forms of coordination devices. *Market* and *hierarchy* are the extreme forms in the spectrum (Williamson, 2005; Ménard, 2012). *Hybrid* governance schemes (including contracting) are an intermediate form in between pure market transactions and hierarchy.

Transactions can be governed by *relational contracts* (Baker et al., 2002) to deal with non-contractibilities. Contractibility will play a key role in modelling since it defines the timing structure of interactions (presence or absence of contracting steps). Non contractibilities raises asymmetric risk exposures and implicitly allocate control rights among the actors in the models. In several research contributions the demand ordering or production decisions are assumed as not contractible but rather the decision variables of a specific actor. Reflection on what should be considered as contractible or not in a model dealing with an eco industrial synergy should be examined carefully since it shapes the eco-industrial park organization and governance through roles definition. The *ownership rights* approach is also a major line of inquiry in the analysis of organizations since it focuses on the repartition of both decision rights in agreed upon arrangements as organizational solutions to the *incompleteness* of contracts (Maskin and Tirole, 1999; Grossman and Hart, 1986). Ownership structures as organizational options design the allocation of decision rights among actors (Nöldeke and Schmidt, 1995). It has been used as a response to commitment issues raised by non-contractibilities in

the literature.

Relational contracts from the economics literature consists in forward looking attitude striving for adaptation to sustain advantages of relationship on non-contractible elements (Baker et al., 2002; Gibbons and Henderson, 2012). Relational governance (informal rules emerging from past relationship) from the sociology of organizations adopts different perspective (Poppo and Zenger, 2002).

Joint ventures have notably been studied following this perspective. Joint Ventures are more relevant than contracting whenever there is uncertainty about performance evaluation and difficulties in monitoring as well as high asset specificity. Incentives alignment can easily arise ex-post without ex-ante explicit specifications of performance requirements (which can be difficult to set). The joint venture concept is then analysed according to three frameworks which are transaction costs, strategic behavior and organizational knowledge in Kogut (1988). There joint ventures can allow for improvements for firms seeking either to acquire or retain tacit knowledge for tailored or unidentified yet value-adding channels. Tsang (2000) proposes a synthesis of the transaction cost and resource based view of joint venture formation. Knowledge (immaterial capital) transfer mechanisms are related to the embeddedness of tacit knowledge (as know-how) in the organization itself since it is not an explicit out-bound transferable informational good. Capabilities improvement due to knowledge transfers is a value driver for a joint venture whereas net alliance costs (transactional, production and managerial) can lower or increase the value of the joint venture over other forms of organization. In accounting for both capabilities and transaction patterns when evaluating the option of joint ventures the author associates transaction cost perspective with the resource based one.

Literature on economic aspects of contracts can be splitted in two parts as the theory of contracts (contract properties and its influence on the relevance of other forms of governance) and the study of specific contracts forms as competitive or coordination tool in specific business contexts.

The latter category of contributions has been investigated in the supply chain literature (see 3.2.2).

As outlined above *Contract theory* investigates the properties of contracts regarding *commitment* and *efficiency* in a transaction cost perspective. Important issue in the study of contracts is their incompleteness considering what elements of the transaction can be contracted or not. Literature on incomplete contracts proposes analysis of the implications of not being able to design and set complete contracts that could handle any kind of contingencies ex-ante. Contracted agreements enforcability depends upon the existance and empowerment of a external court. In order to be enforced the agreed upon provisions must be *verifiable*. Bounded rationality arguments provide explanations on why contracts can not be complete.

Contracts ability to reach *binding* agreements intrinsincally depends upon the ex-post incentives to renegotiate the initial arrangements due to information acquisition or bargaining position change. Regarding commitment (transaction effectiveness) and efficiency (transaction value), the provision of good incentives is warranted especially in case of information asymmetry (non-observability) or ex-ante contextual uncertainties with ex-post resolution. Incentives of an actor are described by his ex-post ability to appropriate value generated from ex-ante provided investments (or efforts). Good incentives allow for ex-ante optimal effort or investment choices. Poor incentives would induce under-optimal ex-ante efforts leading to low value generation.

Transaction can be deterred in extreme situations in which the investments cannot be recovered ex-post because of detrimental economic conditions or opportunistic behavior (like in the so called *hold-up problem*). Moral hazard problems (behavioral oriented) and adverse selection issues (information on product or capabilities characteristics) must be handled in mutual arrangements.

The contractual forms also play an important role in the industrial organization, corporate finance and labour economics literature. When modelling contracting interactions in the industrial organization perspective a *Stackelberg leader* is assumed to be the proposer and thus has a first mover advantage in sequential games so that he can design the best contract anticipating the proposee (follower) behavior. This setting is used in the recent literature on circular economy (Shi et al., 2016) or energy networks (López-Lezama et al., 2011).

3.1.2 Contracting process models: partnering and negotiation

Theoretical models: cooperative games

Regarding negotiations, if the bargaining procedures and the information patterns are detailed and can shape how the offers and counter-offers might be optimally set by actors, the game is considered as non-cooperative this is the case for sequential bargaining (Rubinstein, 1982). Static bargaining games (Nash Jr, 1950; Kalai and Smorodinsky, 1975) rather considered as cooperative since the only strategy available is to accept or reject the interaction (thus reaching the *disagreement point*) and the solution comes from axiomatic requirements on the solution outcomes (note that n-player pure

bargaining games does belong in this class since the agreement must satisfy every players). Cooperative phase for value generation (the achievable outcomes) and a competitive phase for value appropriation co-exist.

Appropriation is achieved either through ex-post bargaining over the surplus or through strategic shaping of the game structure. According to our economics line of inquiry, eco-industrial parks can be seen as a system providing its participants opportunities to play both cooperative and non-cooperative games with each other.

When the cooperation involves more than two actors, the economic problem under consideration should be investigated with suited tools. Coalitional games is a kind of cooperative game in which more than two actors may decide individually to form (to enter) *coalitions* (subset of agents) in order to gain from cooperation.

In some sense the strategic variable is here the commitment to cooperate with a coalition or not. Participation to a coalition affects the value generated by the coalition and thus the achievable outcome for actors (no set of further actions to be taken is specified except the sharing of value).

To model such an economic situation one can assume a given real valued function v mapping coalitions compositions (in terms of members) with the associated generated value. The game is represented in *characteristic form* if the payoff achieved by a coalition depends only on which set of actors belong into the coalition. If this payoff (for any given coalition) also depends on how the members outside the coalition are associated within coalitions the game is under a *partition function form* (Thrall and Lucas, 1963) and allow to model externalities in a coalitional context (Grabisch and Funaki, 2012). Moreover the characteristic function form is intimately related to the underlying assumption of a *superadditive* characteristic function which thus

gives the highest value to the *grand coalition* (the coalition of all the actors). Solutions are proposed to stabilize the grand coalition as it provides the best global outcome.

Different patterns regarding the coalitions formation can be considered. Games with *coalitionnal structure* or *coalition formation games* (Aumann and Dreze, 1974) deals with the emergence of several (mutually exclusive) coalitions. Such pattern can be related to the non-superadditivity property.

Another class of games introduced by Myerson (1977) is *coalitional graph games* in which the internal structure of coalitions (links between agents within a coalition) will affect each agents' payoff. Cooperation in a coalition generates a given value that must be splitted among the coalition's members. An *allocation* of the coalition's value among its participants defines the *payoff vectors* specifying the final gain of each actor. An *imputation* allocates all the value created by a given coalition in such a way that it matches the *individual rationality constraints* (payoff imputed to an agent is greater than what he could have obtained by beeing alone). *Transferable utility* (TU) games assumes that the created value can be splitted and transfered arbitrarily to each member. This feature has been criticized as it cannot represent situations in which actors derive different utility levels from the economic outcome resulting from cooperation. In addition "side-payments" may not be possible to split the created value. In the *Non-transferable utility* (NTU) framework a set of payoff vectors is directly specified for a given coalition (instead of a real valued function in TU-games).

Regarding value repartition issues *Solutions concepts* have been proposed to map a game with its outcome, that is, the coalitions that can emerge and what will be the corresponding (set of) payoffs vectors for actors. The different solution concepts are tailored to deal with the specificities of each type of

game and target specific issues. Solution concepts have characteristic properties. In the Transferable Utility framework the solution concepts developed in the economic literature are the following:

The stable set-(Morgenstern and Von Neumann, 1953). In that solution, forming the grand coalition is a prerequisite for maximal value generation (if superadditivity holds) and further splitting. Thus grand coalition stability must be achieved by deterring any threat of leaving it from any agent. The stable-set is the set of pareto optimal payoffs that is immune to individual deviations.

An important solution proposed is *The core*(Gillies, 1959). The grand coalition stability requires no credible threats of leaving by any agent or group of agents. To ensure its stability the value generated by the grand coalition must be imputed in such a way that no other coalition (subset of agents) can generate enough value for agents in it. In other words the imputations in the core ensures that the payoffs received in the grand coalition for any subset of agents (from individuals to N-1 sized sub-groups) outweigh the total value generated by each of these sub-groups if they would leave the grand coalition to form their coalitions. It is worthnoting at this point that the core may be empty. *Balancedness* of the game will ensure that the core is non-empty (Bondareva-Shapley Theorem). A game is balanced if any convex combination of all coalitions values is lower than the grand coalition value. *Convex games* (with *supermodular* value function) are balanced. Supermodularity referes to situations in which the marginal contribution to value generation of any agent participation is increasing in the size of the coalition she is joining. If a subset of agents included in another larger set, supermodularity is equivalent to the fact that any additional agent brings more value when joining the latter.

Contrary to the core which defined a set of values the solution proposed by Shapley *The Shapley value* (Shapley, 1953) results in a unique value. This solution concept is based on a fairness principle stemming from the consideration of contributions to value creation. It is a way to split the generated value among agents. Fairness is guided by 4 axioms that verifies the Shapley value. The *dummy* axiom requires that an actor whose the contribution is null must earn nothing from value allocation. *Symmetry* requires that the allocation gives the same payoff to actors contributing equally. *Efficiency* states that all the created value must be allocated and *additivity* if different games are played the payoff depends upon the sum of each values. The resulting allocation rule (the Shapley-value solution) gives each agent a payoff that is equal to its average contribution to the coalition. The consideration of the "average" here is fundamental. For any agent its marginal contribution to coalition wealth (can) depend upon which agents are assumed as present in the given coalition before him. Besides the total wealth of a given coalition is fixed entry *ordering* does have an impact on agent's marginal contributions to this wealth generation. Shapley value explicitly considers such an ordering in the coalition structure so that the marginal contribution for any actors can be accounted for in each possible ordering. Marginal contributions are then averaged over those possible orderings and the resulting value attached to any agent is the Shapley value.

The nucleolus (Schmeidler, 1969) is another way to define a value following a bargaining perspective. Schmeidler indeed presents his solution concept as indicating "[...] which point of X is accepted as a compromise between the players". The quality of a compromise is related to the maximal complaint any subset of agents may formulate. Complaints are formalized as *excesses* of the complaining coalitions over a proposed payoff. Excess arise when the

value created by a coalition will outweigh the value which is actually raised by this coalition participants if they accept the proposed payoff (from the grand coalition). Thus nucleolus relaxes the stability requirements of the core. Nevertheless if the core is non-empty no complaints will arise. The nucleolus solution concept proposes a (unique) payoff which minimizes the worst complaints lexicographically (for consistency). After finding proposals minimizing the worst complaint we refine the proposal by minimizing the second worst complaint under the constraint that the refined proposal is consistent with the first minimization. This process executes until a final proposal is derived. This solution is the nucleolus and it lexicographically dominates other allocation proposals.

The kernel (Davis and Maschler, 1965) proposes a solution concept following a bargaining oriented perspective focusing on individuals attitudes over coalition formation. Kernel is always non-empty thus its stability requirements are less restrictive than the core stability. Imputations in the kernel ensures that no agent has asymmetric power over another. Each pair of agents are thus mutually stabilizing since none has any incentive to leave the grand coalition (the kernel payoff) to seek for additional payoff outside because he will not be able to appropriate this additional value since he has symmetric bargaining strength compared to each other agent.

In the Non-transferable utility framework solution concepts have to be adapted since the agents do not derive the same utility from the wealth generated but rather do have *preferences* over coalitions leading to consider payoff vectors instead of a global sharable "value". The core of NTU games is defined as the set of payoffs vectors in the grand coalition that ensures that no coalitions can leave the grand coalition and by doing so proposes to *all* of its constituting agents a payoff higher than the one they could achieve in the

grand coalition. In other words if at least one agent in any of the coalitions is worse-off by leaving the grand coalition then the latter is stable. The set of payoff vectors achievable in the grand coalition that satisfies this condition belong into the core.

Applications

Applications of the abovementioned concepts have been proposed as solutions and analytic tools in a wide range of applications notably in the electricity networks (Lima et al., 2008; Jia and Yokoyama, 2003) and inventory sharing games (Karsten and Basten, 2014). Fiestras-Janeiro et al. (2011) proposed an extensive literature review on fields of applications.

The explicit definition of a *characteristic function* mapping individuals participation in a coalition to this coalition wealth allow for more detailed analysis. An example is given in Reinhardt and Dada (2005) on resource pooling games. Strategic behavior is still modeled in the choice to enter (leave) or not a coalition. If the characteristic function results from the resolution of an optimization program then the action that might be taken by the agents when dealing with this underlying optimization can be thought as a non-cooperative part of the game. The Biform games approach proposed by Brandenburger and Stuart (2007) explicitly deals with this cooperative aspect. In this framework actors behaves in a non-cooperative setting in the first phase of the game in which they have to set their strategic variables choices which will affect (by their interplay) the payoffs achievable in the coalitional game which have to be played in a second stage. The core concept is used to define the solution space of the second stage coalitional games so that by backward induction actors will play the first stage game considering what would be their possible payoff in the core depending on

their strategic choices.

Cost sharing schemes

Various cost sharing schemes have been proposed in the literature. Application of the Shapley value to cost sharing problems is denoted as the *Shapley-Shubik* rule. For single output production function sharing by multiple actors with individual demands one can consider *serial rules* (Moulin and Shenker, 1992) and their adaptations like the *dual serial rule* (Albizuri and Zarzuelo, 2007). A generalization of the serial rules is developed in the *alpha-serial rules* (Albizuri, 2010). Serial rules have been developed by Moulin and Shenker to take into consideration asymmetric responsibilities to average cost return when the cost function is non-linear. Moulin and Shenker proposed the serial cost sharing as a response to limitations of *average cost pricing rule* and its extension to the multi-output case that is the *Aumann-Shapley rule*.

Another set of literature has been developed in the field of operations research. Here, the cost sharing problem is associated to an endogenous cost function from the solution of combinatorial optimization problems as *network design* with application to computer science (Gupta et al., 2008). The aim is to divide costs among the self-interested agents in the system they are part of and which needs to be optimized. The mechanism solution is required to match some properties as *budget balance* (total cost recovery from actors computed contributions) or some fairness principle.

Informational issues in contracting

When dealing with informational disturbed contexts the Principal-Agent models can be used (Laffont and Martimort, 2002). It assumes information asymmetry between a Principal (contract proposer) and an (a set of)

Agent(s) who must perform a task on behalf to the Principal by exerting some costly "effort". Two problems may then arise. *Moral hazard* is related to suboptimal effort by the agent who optimizes its own criteria (minimizing effort) instead of Principal's one. Such a situation appears in context where behavior is hard to monitor since no contracts can be contingent on effective effort provision. An additional issue raised by information asymmetry is *adverse selection* where the Principal is not perfectly informed on Agent's intrinsic characteristics (capabilities, preferences).

An available solution to deal with these issues is to propose a menu of contracts rather than a single contract to the Agent. Appropriate design of the menu of contracts should allow the principal both to match Agents participation constraints and optimize its satisfaction by minimizing *agency costs* (distance to the ideal payoff). In case of adverse selection information is asymmetric and the Principal is less informed than the agent on Agent's specific attributes so that appropriate incentives must be set in order to induce the agent to reveal its private information. Incentives must be provided in case of moral hazard issues.

In our context of eco-industrial parks the synergies arising from cooperation among actors generates a collective value that must be splitted so as to motivate participation to the symbiosis, notably in the case of infrastructure sharing. Thus the right focus must be chosen and the profile of potential participants must be modeled in order to get insights on how do the externalities are generated depending on which sub-set of actors is considered.

Once the situation is well described a need for mechanisms to allocate value and costs among the participants to a common interest activity arises. Indeed each one has an influence on the provision of a service (or a good) as well as on the associated cost of providing it. At the same time each have a

private valuation for the aforementioned service or good.

For eco-industrial parks, depending on actors profiles (supply curves, load curves, quality requirements...) positive and negative externalities can arise when taking part to a collective action as infrastructure or resource sharing.

At this stage we can point out that such individual characteristics (synergies drivers) might be private information leading to potential strategic information retention limiting multi-lateral willingness to commit.

Availability issues like congestion effects or shortages of the shared output or resource must be carefully investigated and properly modelled using suited cost function specifications.

For a given service level or a certain resource quantity the total cost to be incurred by cooperating actors in the eco-industrial park may be lower than the sum of each actor stand-alone cost. To model such synergies *submodular* (concave) cost functions can be used.

Mechanisms deal with information asymmetry between actors involved in a transaction or a joint task. A mechanism consist in a *procedure* which assigns payoffs to agents depending on the *messages* (delivered information) they send to the mechanism. A *Mechanism designer* seek to optimize the functioning of the interactions governed by the mechanism regarding some performance criteria. Loosely speaking designing a mechanism consist in choosing the rules of a game to be played by the actors so that to achieve a desired outcome from this game.

The use of mechanisms thus supposes an inherent hierarchy between the mechanism proposer and the (set of) participants involved.

When dealing with costly production of a commonly used (set of) goods or services appropriate sharing of costs between participants (infrastructure

or technology users) have led to the development of suited concepts and propositions.

Mechanisms outcomes properties are dependant upon the properties of both the cost function which is considered and the *cost sharing scheme* (or method). Cost functions is assumed dependant upon the set of actors using the service or the resource. *Submodularity* in the number of participants is a common assumption since it provides a generic construct to model the value of cooperating (the more actors will cooperate the more the overall cost to be incurred will be low). This is also a key assumption in coalitional games which motivates the emergence of the *grand coalition*. Appropriateness of the mechanism must be understood in line with some designer objectives. Such tools are tailored to adress allocation problems in the context of commons and notably public goods provision. This perspective inherently assumes a hierarchy between the mechanism proposer over the proposees (in fact actors are considered as "Agents" in the literature). Such a framework can be useful in the modeling of eco-industrial parks since it corresponds to situations in which the governance exhibits hierarchy. For instance a large utility provider can build a mechanism to select the best set of potential clients (with private valuation) to be served in the park if infrastructure extension is required and is submodular. Thus the actual symbiosis implementation (heat network extension for instance) will largely depend upon the selected mechanism.

The proposer (designer) thus chooses the best mechanism for him (even if social surplus is the objective it remains intrinsically the designer-planner one and not the participants').

Literature in economics focuses on the axiomatization of cost sharing problems and the development of mechanisms exhibiting specific properties when used to solve specific cost sharing problems. Friedman and Moulin

(1999) proposed three methods for the division of cost incurred for the joint production of heterogeneous outputs and gave an interpretation in terms of surplus sharing. *Cost sharing schemes* are applied on a fixed set of participants and allocate (charges) the cost incurred to the participating agents following some rules. Mechanisms are said to be *induced* by a *cost sharing scheme*.

Mechanism properties are defined and their relationships are investigated. In cost sharing mechanisms three properties are of first importance in line with mechanism design principles (Moulin and Shenker, 2001). A *Budget-balanced* mechanism should allow to recover the cost incurred in the solution provided by the mechanism by means of the charged contributions (what subset of agents to serve and their required contributions). *Incentive compatibility* is another key characteristic of a mechanism since it requires the mechanism to provide a solution in which the actors are willing to set their true (private) valuation for the good (or service) to be produced. It means that under such a mechanism no actor (or subset of actors) has strategic interest to send (purposely) to the mechanism a wrong *message* about their valuation. A mechanism fulfilling this property for each individual actor is called *strategyproof* and if it exhibits the same property for any actors coalitions it is *group strategyproof*.

The third main property is the mechanism *efficiency*. The mechanism indeed chooses the optimal subset of agents to be effectively participating in the activity by balancing each potential participant valuation and cost regarding the designer criteria (for example the net global surplus).

Unfortunately these three properties cannot be met altogether by any mechanism. Thus the modeller and/or the designer must specify which properties

should be guaranteed. In eco-industrial parks, public authorities can subsidize budget unbalanced projects that are efficient thus maximizing the social surplus. Moulin and Shenker (2001) notably investigated the trade-offs between budget balance and efficiency in the case of submodular cost function.

In a multilateral business context (the eco-industrial park) where the proposers will be confound with the proposees due to their strategic autonomy the modeller must be carefull when seeking good mechanisms as long as it does not have the power to impose it unless this mechanism is (itself) an equilibrium choice in the participants gaming. In such cases the governance structure is different from hierarchy and then the recourse to coalitional games can be necessary. Nevertheless a common mechanism (or sharing rule) must be suitable so that the problem is then its mode of selection by stakeholders. Voting procedures potentially influenced by actors financial contributions can be investigated as it is representative of some multilateral governance structures (Project finance, GIE, Joint ventures).

3.2 Contract design framework for industrial symbioses

3.2.1 The use of contracts: Uncertainties and asset specificity in industrial symbioses

Roots of overarching concept of I.E propositions have been formulated by industrial ecologists in drawing parallels between natural and industrial ecosystems functioning. A limitation of those parallels lies in the endogeneity of symbioses because of its industrial (human) nature. Symbioses are set-up by synergy seeking decision makers. Thus two key issues are raised: com-

mitment and efficiency.

Roles are defined along capabilities to exert control over assets, resource flow management, service provision, information gathering and processing. In order to make value generation process efficient behavioral restrictions should apply through appropriate organizational schemes to achieve coordination. Coordination needs increase when the process conduct exhibits externalities and criticality (failure is highly harmful). Coordination devices should be formalized as management policies to which actors must commit to enter the partnership. Actors can find it individually profitable to leave part of their control rights to establish effective and efficient symbioses. It is at this condition that common policy adoption will be stabilized (like in the case of utilities/energy furniture).

1. Industrial symbioses characteristics and the organizational issue

Industrial symbioses are characterized by distinctive features that raise challenges to their implementation. Asset specificity is one of the key feature of industrial symbioses and its influence has been widely studied in the context of bilateral buyer-seller relationships in the economics literature. Several configurations might exist with different degrees of dependence asymmetry (Buvik and Reve, 2001). Anticipated value appropriation imbalances due to post-investment opportunistic behavior (conflictual claims) lower the incentives for actors to complete the deal ex-ante (hold-up problem). Long-term contracting can prevent adverse imbalances by imposing conditions that allow for balanced safeguarding of assets. Nevertheless it comes with drawbacks associated with lock-in and still can be exposed to further ex-post contract renegotiation in case of deep ex-ante business parameters uncertainties in innovation settings (Hart and Moore, 1988) with contracts incompleteness

IS specific driver	risks on	relational effect
Traded quantity	flowrates	contractual warranties
Resource quality	inadequation	process customization

Table 3.1: transactional risks

as a result. Regarding IS uncertainties are strong but since the contract object remain fixed and well identified and the source of disturbances can be anticipated so that related contracts are not incomplete in the sense of Hart and Moore but rather complex. Uncertainties leading to fuzz-up those potential claims are strengthened by the poor by-product quality and irregular availability of resources (and needs) along core activities operating cycles thus making IS implementation more difficult than standard business transactions. To some extent flexibility can be ensured by formalized provisions in contracts (like indexation schemes) or by contingent adaptive behavior allowed in (less formalized) relational contracts. In relational contracts repeated interaction may overcome some of those difficulties but rely on mutual credible threat of leaving the deal which is intrinsically limited by asset specificity in IS opening the way for complex designed contracts instead.

Transactions over synergies in EIPs are induced by private negotiations rather than authoritative centralized allocation schemes or pure market interactions because of the relationship specific informational content required when exchanging non-standard products. A given substitution resource is not homogenous since uses patterns differs from one client actor to another. In order to depart from the bilateral buyer-seller context we must acknowledge that eco-industrial park can be considered as an economy whose technological, political (regulations) and economic characteristics defines a set of

markets with particular market structures that can be endogenously shaped by mutual agreements. In other words what we acknowledge as simple bilateral dyadic relationships (potentially) emerges from a more complex market structure.

A brief review of different *market structures* that can be applicable to an eco-industrial park is necessary to emphasize the strategic content of interactions and the value of dyadic exchanges or multi-lateral coalitions. In a *monopsony* one actor in the demand side faces several potential suppliers. The reverse is a *monopoly* setting where one supplier faces several actors in the demand side. *Bilateral monopolies* refer to situation in which both monopoly and monopsony coexists. In *bilateral oligopoly* market structure few actors are present in both the supply side and the demand side of the market. Such a context is particularly conducive for strategic positioning of each actors. Eco-industrial parks can exhibit different internal market structures depending on the variety and availability of sources, sinks and intermediaries.

Reflections on market structures are important when analysing the set of implemented symbioses. The fact that the EIP is *ex-post* (after strategizing and negotiating) exhibiting bilateral relationships is economically not equivalent to a situation in which only 2 actors are present. As the literature on industrial organization has shown those structures can be also purposely erected by the actors since they can achieve better payoffs by allying (collusion, mergers). The theoretical framework suited to analyse the relations within EIPs and the emergence of effective transactions is game theory.

In *non-cooperative* contexts the agents use their controls (strategic variables) to optimize their individual objectives taking into account the behavior and reactions of other actors. Equilibria are stable and consistent configurations of behaviors that can be reached. Individual preferences over outcomes

(determined from the system state) thus defines preferences over strategies (actions to be taken depending on others' strategies). Many assumptions can be made on the game structure in terms of decision timing (sequential, simultaneous) and information availability. In *cooperative games* binding agreements can be decided adopting a satisficing perspective. Cooperation in such an economics context do not have any "moral" content it just emphasises that actors can generate surplus by reaching a binding agreement. Competition on the contrary leads to struggle for a given surplus appropriation as in Bertrand price competition models in which the winner takes-all. Buyer-seller relationship can be considered using the cooperative setting even in the absence of any further collaborative attitudes because in absence of any agreement no surplus is generated. A distinction between cooperative and non-cooperative settings lies in the modelling of players actions as acknowledged by Brandenburger (Brandenburger, 2007) from Aumann's reflections (Aumann, 1989). The former approach is actions-oriented (procedural as proposed by Brandenburger) whereas the latter is more outcome oriented (combinatorial). Bargaining games are considered either as cooperative games or non-cooperative games depending on the description of the game environment.

Consequently EIP internal market structure refers to the underlying network of potential trades. It is characterized by the number of agents in each echelon as well as the existing potential connections among them (in its simplest expression a bipartite graph). Quality issues due to misspecification of deposits as substitution resources can dramatically affect this within EIP market structure (for instance the relative distance for steam transfers may hinder some linkages and allow other). The market positions of any actor can be more or less favourable depending on its relative endowments (quan-

tity issue) regarding tradable resources and demand size from downstream users. Market positions affect bargaining outcomes and ex-post opportunistic claims since it is shaping dependencies. Information on network structure can be public or incomplete. The first case can give a simple representation of "planned" eco-industrial developments (like Ulsan EIP) for which information comes to each participant due to planner territorial diagnosis, communications and collective meetings. On the opposite, self-organized IS (like Kalundborg) emerges from private negotiations within an undefined network structure leading to a model integrating the assumption of incomplete information on the set of potential participants and their relative positions.

Implications for economic analysis

Coalition-based reasoning can be applied to multiple-user contexts such as infrastructure and service sharing strategies since it allow to understand endogenous strategic group formation taking into consideration "stability" requirements (given by solution concepts from cooperative game theory). Such a collective action must be sustained by stable mutual gains. Coordination must allow to achieve the best outcome (like mitigating congestion effects) while value sharing mechanisms have to be set to ensure appropriate surplus repartition. Mechanism design theory supposes hierarchy between the mechanism proposer (designer) and the subordinated agents. It is *a priori* not appropriate for studying EIP because of the commitment issue (Figure 3.1). At least a mechanism should first be agreed upon before being implemented. Moreover it poses the question of criteria to use since it is collective action driven but not a principal's objective (like state owned utilities). Strategic decision making on different market structures must be investigated in order to highlight how the symbioses implementation outcomes and effectiveness

will be affected by competing or cooperating actors. Moreover, asymmetric cost structures and willingness-to-pay for the substitution resource must be assumed since by-product value can be different from an industry to another. Depending on contextual assumptions on parameter values and uncertainties regarding market prices, symbioses costs and by-product volumes several transactions might emerge. Regarding contracts, pricing decisions and risk sharing using contractual provisions must be analysed under those different contextual assumptions in order to understand how external parameters will shape the equilibrium arrangements. Organizational patterns are thus related to those elements so that some forms are likely to be more appropriate. Joint Ventures capital expenditures, verifiability, high embeddedness (social view), no opportunistic behavior, knowledge technology transfers (even developemnt). Long term contract is the most suited tool in this information intensive transactions requiring important relationship specific assets and routines while less formalized shorter term contracts can be used when investment and informational content is low. Failure to find such arrangements (value sharing) or fonctionnal misalign-

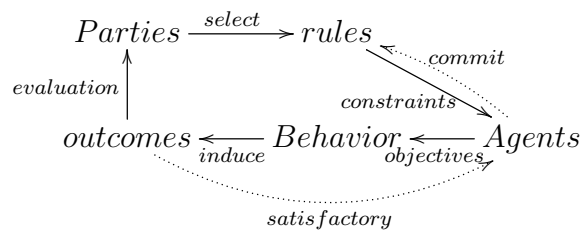


Figure 3.1: Commitment to a contract in IS

ments (coordination issue) can limit the incentives to participate in such a collective (or bilateral) action resulting in synergy project collapse despite concrete opportunities.

Contract design will be investigated in the subsequent section of our work.

3.2.2 Contracts architecture: lessons from the literature

Contracts and transaction forms

Contracts are embedded in more general business model of the transaction. In a first step we will thus quickly review the types of business models de-

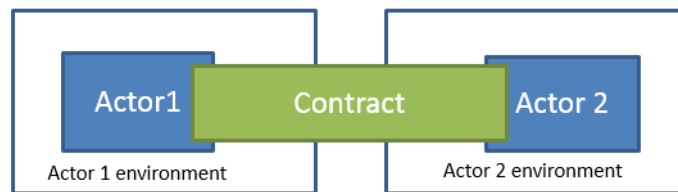


Figure 3.2: Transactional environment

scribed in the literature to shape the global picture of the transaction before entering into contractual details bridging actors objectives and environments (Figure 3.2). The Product-Service Systems framework (Tukker, 2004) offers different types of business objects over which transactions can be set-up. As we will explain, following Tukker's work on those forms, ownership is a key dimension of such systems characterization. We translate Tukker's vision with the economic concept of rivalry to go into the details of the proposed forms. The basic contract types that we will use to model economic relationships between actors depend upon the modelled transaction.

a) Types of Product-Service systems: transactions object and scope

In the first system (*Product-oriented*) ownership is defined over a given product and transferred during the transaction. Product will be valued regarding the benefits achievable using the full property of the exchanged product.

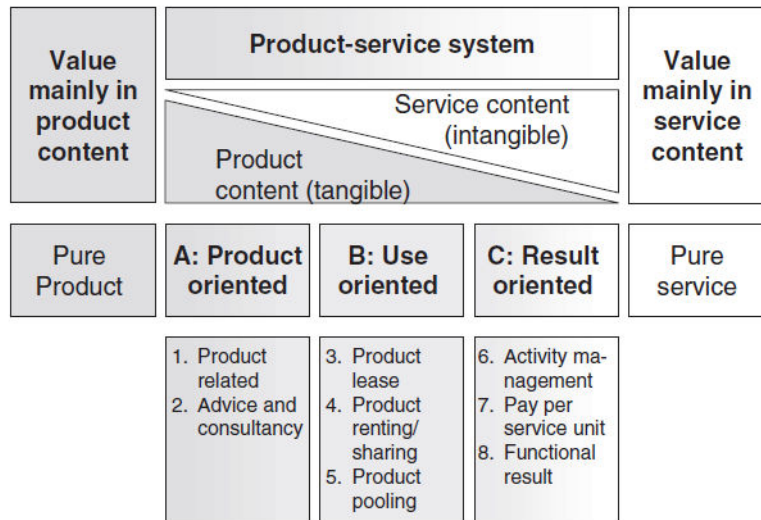


Figure 3.3: the PSS framework (from Tukker, 2004)

Services can be attached to the transaction to ease the use of the sold product. The transaction is then organized along a *Supply contract* with property transfer

Use-oriented systems are valued by the targeted use of a given capacity.

The client can customize its use patterns within the limits set by the constraints defined by the specifications of the equipment or means available to him. Different forms of Use-oriented models exists depending on the rivalry over the capacity to be used by potentially multiple users.

A first case is the *lease* form which is characterized by full exclusivity. That is the specificity of the leasing system. The transaction does not include property transfer but transfers all the use rights to the lessee who can access and use the item without constraints from other potential users (no-rivalry). In systems based on *renting*, rivalry exists for access but not for use. Multiple users can benefit from the item related services but sequentially. Thus there

is a rivalry in the access to the item but once accessed there is not rivalry in-use while in the *pooling* system rivalry for use arises whenever the use-level overcomes the peak-capacity level of the item. Clients within the pool can use the item at stake simultaneously.

A third archetype is the *result-oriented* PSS. In such a system the means are not at stake for the client since they are managed by the service provider in order to match at best (and at least cost) a targeted performance level.

In the *service-unit* concept, the use level can be unitized and can be variable in time so that the service "quantity" can be accounted for and then be paid accordingly. Note that this does not imply the selling (property transfer) of any product.

A last type is *functional result*. This system can be applied whenever the performance must be completed globally following pre-defined specification. The implementation of such PSS requires a contracting phase that will be shaped by several transactional characteristics as ownership structure, client role and use patterns, supplier/provider role and capabilities and required performance.

In addition to the product, service or product-service system focus, literature expanded the scope of business transaction characterization to the way actors would interact within the whole business model (Lay et al., 2009).

As a consequence, the form of contracts can be related to different business models.

The combination of those elements characterize the transaction environment.

Ownership of equipments or assets can belong to one actor at stake in the product or service exchange (manufacturer who designs the equipments or customer who uses it). Ownership can also be held by tiers like banks who do

Characteristic Features		Options			
<i>Ownership</i>	<i>during phase of use</i>	Equipment producer	Leasing bank	Operating joint venture	Customer
	<i>after phase of use</i>	Equipment producer	Leasing bank	Operating joint venture	Customer
<i>Personnel</i>	<i>Manufacturing</i>	Equipment producer	Operating joint venture	Customer	
	<i>Maintenance</i>	Equipment producer	Operating joint venture	Customer	
<i>Location of operation</i>		Equipment producer's establishment	Establishment "fence to fence" to the customer	Customer's establishment	
<i>Single / multiple customer operation</i>		In parallel operation for multiple customers		Operation for a single customer	
<i>Payment model</i>		pay per unit	pay for availability	fixed rate	pay for equipment

Figure 3.4: Business concepts framework (from Lay et al., 2009)

not have any technical capabilities but provides a financing scheme over the asset production and use. Mixed ownership can also be used (what is denoted as operating joint venture in Lay's framework). In that case many actors do have ownership rights over it. The capabilities endowments of actors regarding the performance completion then induce different workflow patterns that again can be totally or partially operated by business stakeholders. Localisation is another element and is determined by technical constraints. The number of actors by echelon (supplier or customer) is also important to clearly define the business model and governance schemes applicable. Regarding IS, infrastructure sharing will belong in the left-hand part of Lay's framework while dyadic supplier-buyer relationship will be on the right hand side.

Finally the "payment model" will be embedded in contracts and shaped by specificities of the PSS to be considered in a transaction.

We will analyse and develop this last element in detail in the forthcoming section about contractual guidelines for IS.

Another useful stream of literature characterizes organisational forms of transactions depicting the roles of actors and their evolutions for large and multi-stakeholders investments in infrastructures. The *project finance* framework is an architecture in which the liabilities do not affect firms core assets by creating a *Special Purpose Vehicle* associated to a project. This framework is useful to structure the possible interplay of many actors and contracts along a project lifecycle. We thus review and detail the functioning of this specific form of partnership to acknowledge its utility and gain insight on transactional environment description. Project finance exhibit specificities of in comparison to equity or classical debt financing. The project have to be understood as autonomous and legally distinct from the sponsor company (thus not exposed to recourse on firms assets). The collateral for loans is the asset tailored to the project which is off-balance sheet. Cash flow and project specific assets are the only elements under consideration for loan attribution. Complex contracts must be designed to allocate risks among project stakeholders (Farrell, 2003). Project stakeholders can be identified regarding their role and interest in the project completion and results. *Sponsors* are project's equity investors whose the contribution is associated to *lenders* for financing the infrastructure which is built-up by a set of *engineering, procurement and construction contractors* (EPC). *Suppliers* for inputs provision are also involved in the process as the infrastructure running constitutes sales prospects. *Operation and maintenance contractors* also refered as *operators* use their suited capabilities to manage the infrastructure operations. The *Offtaker* is the final client of the infrastructure based activities. Off-take contracts are established in order to partly secure future cash-flows. Stakeholders faces different risks or benefits depending on the project phase and element at stake. Project finance structure is a complex multi-lateral

instrument used for financing highly capital intensive projects and is notably used in *public private partnerships* (PPP) for public infrastructure setting. As such projects (either private or PPP) are characterized by large up-front costs for building phase, long-term lifespan for its exploitation phase and high asset specificity complex contracts are designed. Ownership rights are transferred along the project life-cycle following different schemes. In the *Build-operate-transfer* (BOT) schemes the private shareholders are responsible for project completion and owns the asset that they will operate (or make operate) after construction in order to recover the capital and earn margins. The service is managed by the project owner who earns corresponding benefits and faces exploitation risks. Agreements specify delay and conditions triggering assets transfer to the public authority. Another scheme is the *build-lease-transfer* where the project owner does lease the operation to the authority and recovers capital through revenues from leasing. Exploitation is under the responsibility of the authority (this is the key difference with BOT partnerships). Ownership is transferred at a predefined price when agreed upon conditions are met. *Operating-lease* contracts are used when the infrastructure already exists after construction completion. It can be also observed after the transfer of ownership to the contracting authority. Project financing arrangements are embedded in those partnership agreements.

Transactions governance forms

The net of contracts and rights interlinking parties in an industrial symbiosis context can be extended from generic and classical forms depicted in the frameworks described hereabove. First of all a set of rights are associated to various elements at stake in a transaction. The basic elements will consist in assets (means to achieve a performance or resource production), resources,

Updating the conceptual premises

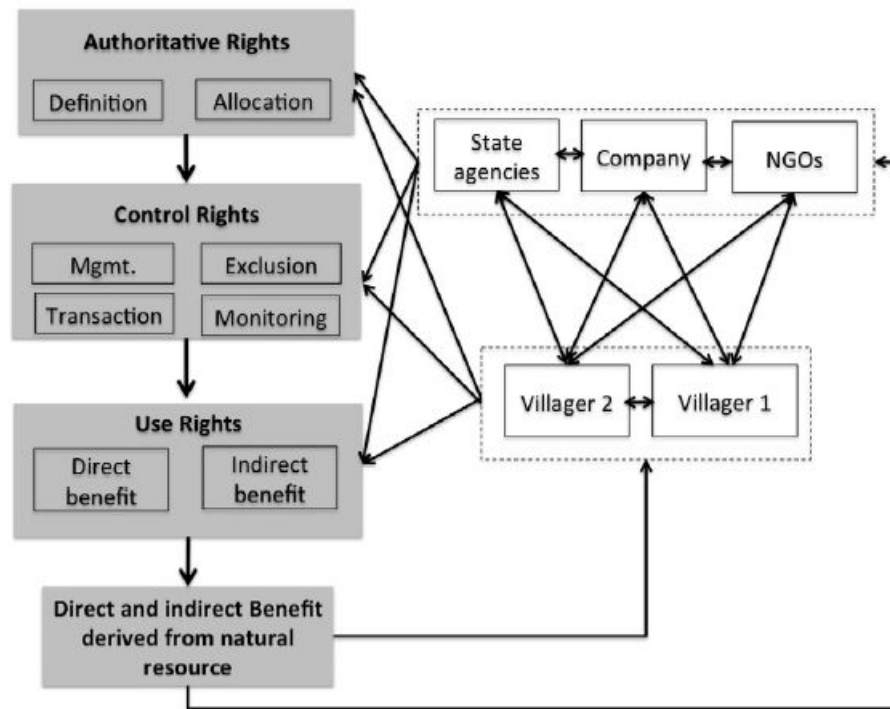


Figure 3.5: Property rights regimes (from Sikor et al., 2016)

capabilities and payments. A governance structure is shaped by ownership and will affect decision/action rights over those basic elements for different (set of) actors. A recent theoretical framework have been developed as an extension of Schlager and Ostrom (1992) seminal work on common pool resource governance (Sikor et al., 2017). This framework is depicted in Figure 3.5. In this perspective, "property rights regimes" structure the governance form of transactions along 3 hierarchically interrelated categories of rights. We simplify this framework and will retain only ownership as implying authoritative rights, the other rights being transacted upon in function of the capabilities mastered, the resources available and the asset owned.

As a consequence, various forms of governance structures can be used when dealing with industrial symbioses. While an infinity of forms can be generated using the theoretical frameworks reviewed from the literature we will propose forms that target the key elements of industrial symbiosis transactions.

We will simplify those frameworks and treat stakeholders as "Buyers/users", "suppliers/providers" or "auxilliary".

Focusing on resource substitution synergies, we will propose potential structures insisting on the roles of each involved actor.

Structure-1: Self made final resource supply/per-unit service

In this structure the tangible substitution resource is transferred (with or without ownership transfer) and the capability and assets belongs to the supplier. Customization is made by the supplier with respect to the contracted bill-of-specification. The user/buyer then substitutes its standard resource (or service) and derives cost savings from it. Those savings allow her to pay the supplier for unit-costs incurred and fixed costs associated to the investment and maintenance of the assets needed to access and customize the substitution resource.

Structure-2: Final resource supply/per-unit service using auxiliary actor

In this structure the tangible substitution resource is transferred (with or without ownership transfer) from the source supplier to an auxiliary actor. The assets belongs either to the supplier or the auxiliary actor. The capability is mastered by the auxiliary actor only. Customization is made by the auxilliary with respect to the contracted bill-of-specification. The user/buyer then substitutes its standard resource (or service) and derives cost savings

from it. Those savings allow her to pay either the supplier or the auxiliary for unit-costs incurred and fixed costs associated to the investment and maintenance of the assets needed to access and customize the substitution resource. In case the raw substitution resource is sold to the auxiliary he is paid by the user/buyer. The auxiliary is the first order buyer of the raw resource supplier. In case the final substitution resource property belongs to the supplier, the buyer/user pays the source supplier who in turn pays the auxiliary actor for its customization service on a pay-per-service-unit basis (Custom work case).

Structure-3: Basic resource supply

Here the tangible substitution resource is transferred (with ownership transfer). Then customization tasks are performed by the buyer who masters the capabilities required to convert the raw substitution resource into a usable customized one. Buyer derives benefits from savings less the costs he incurs to perform the customization steps. The supplier is paid on a pay-per-unit scheme on the basis of the access and transportation costs only.

Structure-4: intermediate resource supply

This last structure is a mix of the formers. Indeed customization can be partly done by the supplier and the remaining part of operations performed on an intermediate resource by the user itself. In that case part of the investment cost are beard by each actor.

Focusing now on infrastructure sharing synergies, such symbiosis projects usually require larger investments and are intrinsically characterized by multiple users or stakeholders at one echelon (suppliers, users).

To govern such transactions actors might use complex set of contracts for the infrastructure to be erected and/or managed. Key elements are related to

asset ownership regime (assets/resources targeted and decision power repartition rules), resource access scheme (decisions regarding sourcing and resource customization patterns) and the nature of the PSS (resource selling or service provision).

Structure-1: Self-investment with activity management outsourcing

Asset ownership belongs to (a subset) of the the users (or clients) but operational management of the asset is outsourced to a tailored service company (the auxiliary actor). Strategic decisions belong to the pool of asset owners. Strategic changes such as auxiliary actor contracting, sourcing strategy and pool members evolutions can be managed in agreed upon cooperation rules. The service provider can be in charge of resource acquisition (at least cost) or not. If yes, she will charge the pool of users/clients with the unit costs derived from the purchasing of inputs and energy. If not, the management of operations is her role but the resources she can use are sourced and chosen by the asset owners-users but not by pure "external" users. To gain strategic decision making the users might buy shares of the asset if applicable or pay a fixed fee (contribution to the pool) that might be decreasing in the pool size.

The users then pay the auxiliary actor a fixed rate for the service including fixed costs of maintenance and variable costs (excluded the owned sourced resources) on a pay-per-unit basis.

The cost of investment is not paid to the service provider but rather to the owners who invested. This cost beeing paid by actors joining the pool or by external users paying a periodical fixed fee based on the capacity they contract upon. This flexibility of sourcing options allow to leverage the bargaining positions and technical expertise of either the auxiliary actor or the

pool of clients.

Structure-2: Investment and self activity management and supply contract portfolio (product or service-unit)

In this case no auxiliary actor is involved. Asset owners do have the capabilities to operate this and use it. Then they propose supply contracts to clients in order to use the available capacity at best.

The clients will pay for the service performed or product supplied on a pay-per-unit basis and pay an access price based on the required capacity. Additional contracts signed-up with new users can allow to lower the access price part of the payment for entrants and already committed users.

The content of contracts: Contractual provisions

Contracts and their provisions have been extensively studied in the supply chain literature and are regarded as cost-cutting coordination tools and risk sharing devices. Contracts interacts with planning of production or replenishment policies and ordering. In the supply chain literature the commitment to produce or buy is either assumed as contractible (forced compliance) or conditional on incentives (voluntary compliance) while commitment to the transaction is assumed as given (Mathur and Shah, 2008). Supply chain literature thus offers a good complement to economic literature because it focuses more on efficiency and risk sharing aspects of contractual provisions (Govindan et al., 2013). One classic model to investigate the impact of different contractual provisions on a given supply chain performance is the *Newsboy problem*. This simple model is used as the baseline framework in the supply chain literature on contracting since it emphasises both the cost of unsold

(but costly produced) items but also the opportunity cost (and direct costs) of not matching existing demands from the market.

At this point we must acknowledge that the business contexts of discrete products manufacturing differs from some process industries or the utility and energy production ones (which are of first interest in industrial ecology) because the final product is storable and the operating part of its production costs (notably its variable cost) is incurred before the demand is known. In energy production or utilities supply this is not the case. Production takes place when orders are formulated simultaneously. Thus in the latter the capacity is the focal point for supply chain analysis rather than the carrying cost. Regarding our line of inquiry contract design will not target as a priority the risk of carrying useless inventories or incurring sunk variable costs but rather on how to use production capacity and generating mutually profitable resource exchange to trigger commitment to the contract.

Contracts are built with a set of elements whose the combination define the properties of the contract as a risk and value sharing and coordination tool. Contributions have investigated the influence of some contractual devices in particular supply chain settings (for extensive literature reviews see Cachon, 2003; Gomez-Padilla et al., 2005; Govindan et al., 2013).

Among those provisions, *tariff* is the key part of a contractual arrangement in economics and supply chain literature. It specifies how the value is transferred through *payment schedules* structured by a *price* which is paid according to a rule associated with some performance over a given contractual object (delivery, production, reservation, availability). Payment for delivery must differ from production since the former requires additional steps to be completed thus the consideration of additional costs and risks. In the same way reservation (pay for availability) induce an opportunity cost for the supplier who

commit not to use the reserved capacity even if it was more profitable for him to reallocate its means. Availability is thus costly and must be priced accordingly. The most used pricing scheme in the literature is the simple linear *wholesale price* structure (with fixed unit price).

In dynamic contexts this unit price can be indexed over other items prices. As we will show this tool will be useful to reflect both the unit cost of producing the wholesale priced good and to match the moving price of the alternative in resource substitution synergies. *Indexation schemes* then allow for safeguarding mutual beneficial exchange. Some limitations must be set in order to avoid large fluctuations or one-sided detrimental effects otherwise renegotiation can arise and its anticipation will increase the transaction costs. Another widely studied pricing scheme is the *two-part tariffs* (Hubbard and Weiner, 1986). Two part tariffs are composed of a variable part (wholesale price) and a fixed part (the *fixed fee* or *franchise-fee*). Such a tariff have been demonstrated to be a tool for surplus extraction by monopolists or Stackelberg leaders in (deterministic) buyer-seller contexts since it allow the contract proposer to not distort the incentives of the proposee to set its optimal quantity order. Indeed the fixed-part does not interacts with the proposee's *first order conditions*. Two-part tariff is a *non-linear pricing* scheme. Other forms of non-linear pricing schemes are the variations of *quantity discount* contracts. In such schemes the wholesale price paid is not constant in the quantity ordered. Different (an infinity of) structures can apply depending on how the quantity ordered affects the total price paid. Usually tresholds are pre-specified in the contract so that depending on what quantity will be ordered different treshold will be reached and the corresponding rules will apply. Two generic schemes differs in that either the unit price resulting from the quantity discounts applicable in a range of orders will apply on the total

ordered quantity or rather apply just for the marginal quantity associated to the range.

The consideration of various risks in transactions supports the use of additional contractual provisions.

Indeed production or delivery quantity levels can be at risk due to several triggers. Supply limitation can be partial (shortage) or total (disruption). Such risks notably foster the use of Back-up supply contracts (Zeng and Xia, 2015). In the supply chain literature (focusing on inventory cost limitation) lead-times are also considered as risky (Bandaly et al., 2016).

On the other side, ordered quantity level can be at risk for various reasons. To cope with those risks tariff definition is completed by *quantity-based* contractual terms that are notably used in risk sharing contracts.

Notably, the *Minimum-Bill/Take-or-Pay* provisions (Masten, 1988) do have risk sharing properties different from the lump-sum part of two-part tariffs pricing schemes regarding efficiency and incentives. In presence of uncertainties *minimum quantity* agreements can secure the supplier in case of demand side risk (Tibben-Lembke, 2004). Here appears a distinction between storable goods supply chains and just-in-time continuous process industries (like utility or energy). If final demand is ex-post lower than the supplied quantity inventories must be carried by either the producer or the client firm unless an arrangement specifies a sharing of those unsold inventories between the producer and the client firm as in *buyback* contracts. In such an arrangement the products are delivered to the client firm according to its ordering before the selling season (before information resolution). Residual unsold inventories are then splitted between the two contractors according to a rule specifying which amount should be returned to the supplier and at which price (i.e: cost for the supplier). The role of unsold inventories in the case of

utilities and energy production is played by useless (over)capacities.

Compensations to the buyer in case of supply side risk consists in *penalties* that can be imposed in case of not fulfilling the contracted deliveries. The penalties for not fulfilling a contracted supply can consist in arrangements in which the supplier pays for the clients expansive back-up supplies. If the production is interrupted and lost sales arise the penalties can be indexed upon market prices. Mathur and Shah (2008) proposed a model integrating two-ways penalties in a supplier-manufacturer model with demand uncertainty. Penalty is dependant upon difference on actual orders (resp.deliveries) and contracted target capacity reservation level (resp.contracted quantity).

Decisional flexibility is at the core of *option contracts*. *Call option contracts* consists in the purchasing of a right to purchase in the future a certain amount of a given item at an pre-agreed price which is called the *exercice price* or *strike price*. The purchasing price of the right itself (that is the option) is called the *option price*. Thus the option price actually depends on which gains are expected from postponing the item purchasing decision. This gain is dependant upon future economic context but also on the interplay between the decision relevant external parameters with the contracted strike price. Option contracts must play an important role in industrial symbioses based on substitution strategies since it allow to share risks related to ex-ante fuzzy information on the relevance of purchasing the substitution input in comparison to the alternative item. Such option contracts are suitable in the case of continuous production like utilities and energy since it does not imply pre-production but rather pre-commitment (Wu et al., 2002). The supplier can influence ex-post revenues by setting a more competitive strike price but he can also balance uncertain ex-post revenues with certain (ex-ante) one by obtaining a higher option price.

As we mentioned earlier, availability (of a resource or a mean) is a valuable "service" that can be transacted upon. *Capacity reservation* contracts allow for the access of an agreed upon supply capacity in the future and share some similarities with options (Spinler and Huchzermeier, 2006). Those contracts thus price and delineates the abovementioned availability service. The main difference is that capacity reservation does not specify a quantity to be purchase but rather a right on the maximum quantity (the capacity) and thus allow for more flexibility. When several clients use such instruments the price or residual capacities can evolve depending on global reservations. Flexibility plays a key role in such arrangements due to incomplete information on the state of the world. Different policies can be considered in terms of contractual flexibility to enhance planning efficiency (Bassok and Anupindi, 2008). In *rolling horizon planning* environments order flexibility can be bounded in order to avoid disturbances (Tsay and Lovejoy, 1999). In addition to the postponement gains (information acquisition) contractual arrangements can also prevent supply unavailability by ex-ante commitments (Serel, 2007).

In the following we will propose a contract architecture and a set of contractual provisions design in order to provide a guideline to ease the contracting for industrial symbiosis transactions notably resource substitution synergies.

Generic contract architecture

Contracts do transfer value to actors according synergistic cooperative drivers and the split of the resulting surplus (competition for appropriation).

Contracts are characterized by architectures which supports various economic properties. Summarizing those elements on contract architecture leads to obtain a simplified structure to deal with central issues regarding eco-industrial

symbioses transactions.

At this point, let's indicate that important structural elements of contracts will be considered as peripheric to our study since it concerns legal issues (legal validity, formal issues). We rather focus on the economic content of contracts.

We thus propose a generic architecture insisting on its interplay with the transaction value.

This architecture is defined along contractual "slots" that must be "filled" with a set of tailored provisions that will be detailed in the subsequent part of our work.

- *Contracting parties:*

A first element to consider is the set of actors that will make binding commitments signing-up the contract. It is indeed a first step to characterize the economic problem rose by contracting. Some peripheric actors may have an exogenous influence in the process of contracting but are not taking the commitment decision associated with the contract at stake.

- *Contract object:*

The second notion is contract's *object* which delineates the scope of application of the agreed terms. Following this, a contract is relative to the realization of a set of *performances* (supply, service, conversions...) tailored to satisfy a need and specifying what actions supports the *value proposition* at the root of a transaction.

- *Bill-of-specifications:*

Performance is thus described in the *bill of specifications* which affects the transaction through the contract object.

We can model its influence using various constraints regarding interconnections, quality or available quantities.

- *Tarification-payments:*

The *tarification* part is then of first interest in our study since it fixes the obligations of actors regarding direct value flows in monetary terms between contractors. Tarification is defined by provisions indicating the agreed relationship between performance status (counterpart of the payment) and the resulting payments. Those relationships are expressed in terms of monetary and physical amounts, procedures, revision formulas, information transmission or penalties and warranties.

Those blocs then define *obligations* for contractors which are translated as constraints on their behavior and results of such constrained behavior. Contracts thus shape the value flows mechanics in-between actors in accordance with contractual dispositions and the exogenous conditions given by the economic environment following the symbiosis business model at stake in the transaction (*revenue model, cost model, value proposition*). Focusing on the economic content of contracts, tarification will be our main unit of analysis. Tarification applies to different provisions.

- *Duration and end-of-contract Provisions (termination):*

Such elements can be included implicitly (individual rationality, performance targets, property rights transfers).

Thus we will focus on the variety of pricing schemes application to performances and warranties for both the buyer and the seller.

3.2.3 Substitution synergies as a multi-period buyer-seller relationship

Actors objectives and behavior

Economic modeling of resource substitution must allow to highlight the way individual behavior by actors will shape the symbioses implementation and the value repartition among participants. In other words this research work will investigate the implementation mechanics of symbioses in eco-industrial parks by considering its participants as interacting individual decision makers rather than networked technical devices.

Thus in order to not depart from an economics approach of eco-industrial parks a part of our contribution will be to derive appropriate constructs to be used in the models setting in order to perform economics-based investigations that are consistent with short term issues faced by actors. We dont propose supply chain literature alike research contribution focusing on inventory models that we thus consider out of scope.

The baseline framework for industrial organization modelling is to use a timing structure for the problem description. Several steps are sequenced in time so that interactive decision making situations can be modeled. Exogenous information revelation can be added in the sequence of events to model context related uncertainties and information asymmetries. Decision points are indicated for each actor and decisions can be taken simultaneously or not allowing to model different informational structures. If a step consists in playing a game with simultaneous decision making *normal form* game can be used as a modelling tool. On the contrary if the game to be played exhibits sequenced actions by the players an *extensive form* representation can be used.

Usual timing structures assumes that contracting and investment decisions are taken in the first steps. Contextual information modelled as parameters can be made available in different steps. A common trick consist in assuming a step "0" in which *nature* delivers information. Information can evolve across the steps. Ex-ante knowledge in the form of a probability distribution over parameters values or over a set of discrete scenarii can be assumed. Risk and uncertainties exposure modelling will be associated with decision timings defining who decides, on which control and under which *information sets*. The way actors are facing those risks and uncertainties shape the economic problem. Risk and uncertainties over relevant elements as demand, costs, prices, resource availability, technology efficiency can be modeled and integrated in the sequence.

Symbioses implementation effectiveness (what effective exchanges results from interactive decision making) and synergies efficiency will guide our reflections. Symbioses implementation mechanics in the eco-industrial park have to be understood regarding relevant stakes influencing eco-industrial synergies.

Our research is striving for complementing existing literature on industrial symbioses by adopting a bottom-up approach since organizational design will be assumed as endogenous or at least top-down propositions formulations will be required to be consistent with this co-existing mechanics.

As stated above, risk modeling can be performed using probability distribution over parameters values or through structured scenarii with discrete probability distribution. Scenario building will be of first importance to represent the different states of the world (the context) which must be decision relevant for the actors.

To do so, we frame our object of study with a multi-period buyer-seller

framework (Figure 3.6).

model framework notations

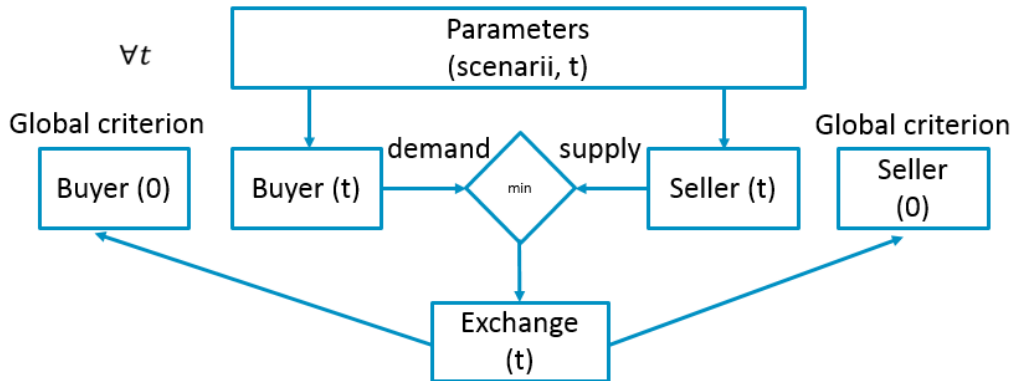


Figure 3.6: Multi-period Buyer-Seller framework

Buyer and Seller objectives

The issue of mutual commitment to the contract:

Since symbiosis requires investments its profitability will be considered over an activity *horizon* leading to identify which aggregation level is at stake.

In the Global (whole horizon), long-range planning decisions (investments) do frame the shorter range decision making degrees of freedom pertaining to operational flow management in every periods ("t") of the horizon as depicted in Figure 3.6.

Project value is generated incrementally along those resources and cash flows. A binding contract will be signed (in period "0") if for each actor it generates (ex-ante) satisficing expected outcomes. Satisfactory conditions can be modelled the following ways taking into account the assumptions regarding

contractors attitudes towards risk (aversion or neutrality) and the tailored criteria that must be modelled accordingly. Applicable approaches can include:

Expectation-based approach, compensation:

Expectation-based criteria such as *Expected* profit, cost, net-present-value are usually used in the literature. The net-present-value does have links with the profit function (savings or sales) but introduce the time-value of money within computations. The methodological difference stands in the use of simulations over a specified horizon in the case of NPV against the use of an analytic expression of profit. The former is more computational than the latter. The reason of using NPV computations rather than direct analytic expressions lies in the rich description allowed for information dynamics. This is particularly relevant when detailed controls planning and sequencing is important (supply chain approaches due to inventory management issues) but aggregating those effects in a synthetic criterion can be sufficient in some class of economic problems.

Other criteria as value at risk, conditional value at risk (of NPV or other economic criteria) can be also used when statistical information knowledge (probability distributions) about economic parameters of the transaction is assumed.

Note that if no statistical information would be assumed decision criteria under uncertainty (not risk) can be proposed to evaluate decision options like *regret* minimization or the *maximin* outcome or *Chance constraint* models. The introduction of *Robustness* objective for the decision makers can be also investigated in order to depart from the usual expectation based approaches.

Chance constraint, frequent satisfaction:

All the contract designs that satisfy global profitability in a certain percent-

age of scenarii will be signed.

We let investigations on contracting based on those last criteria for further research. We also think that it could be insightful to use mixed criteria.

All that matters when defining the appropriate criteria (measure) and objectives (preferences) is to target the right problem-specific decision relevant terms. Here aggregated measures are considered since we target a commitment problem related to the expected value achievable from an initial investment.

In the following we will use Expected profit based approach to investigate the contract design problem raised by resource substitution synergies.

Risks in resource substitution: exogenous vs endogenous

In order to address the main issues raised by industrial symbioses the models must carefully represent substitution input demands functions that can be price dependant. Indeed, since the user faces both the prices of the substitution input and the alternative one its purchasing decisions and sourcing policy will be affected by the contract. Price dependant demand functions for an input raises the question of the input mix properties in terms of complementarity and degree of substitutability as well as the order flexibility (potentially contractible) to model sourcing options. Thus the construct must represent the impact of the total demand for the available substitution input when its price can affect the demand. Note that such assumption suggests some flexibility (possibility along some degree) in the ordering process of the client enterprise but its explicit modelling or optimization can be avoided. In a Bertrand setting (price competition) the problem is simplified as the demand is either null or unitary.

Transaction value is fuzz-up by uncertainties associated with standard in-

put prices on one hand and by-product unit cost (production, pre-treatment, transfer) on the other hand. Such uncertainties must be included in the model. The cross-effects of partners investments on costs does have an impact on incentives to cooperate and on the investment level so that it is a characteristic feature of industrial symbiosis which increases the degree of asset specificity. Uncertainties or risks regarding the effective investments effects on variable costs reductions have been considered in the literature (Che and Hausch, 1999) and will be implicitly included in our models since technologies for product recovery and the quality of by-products is difficult to anticipate. We model this within the risk of resource shortage or unexpected cost increments.

The potential value of substitution resources exchanges must be considered as uncertain since it depends on cost parameters and resource/needs volumes directly related to the core activities intensity. Substitution resource supply function must be modelled as depending upon ex-ante uncertain cost parameters(production costs)and uncertain deposits volumes because by-product supplies depends on the supplier core activities dynamism. Decision relevant drivers have to be identified to propose a relevant generic economic-decision problem. When dealing with the choice of cost structures the modeller must establish which aggregation level is relevant from careful transaction related elements identification.

Capital expenditures on capacity choices are relevant since it relates to the most strategic decision and must be included. Capacity choices will interact with the timing structure since it is a bet on (aggregated) future needs that must be not perfectly known at the time of decision (see chapter 4 for extensive analysis). Differencies in operating costs depending on the initial investments can also be important in an economic setting as it affects overall

future (not perfectly known ex-ante) surplus creation.

Assumptions on actors interactions patterns are a major feature of economic models. The modeller has then to adress the question of what is contractible or not in the model. On elementary parts of the economic models several constructs have to be built to provide suitable investigation tools. The elaboration of those constructs is an important part of the model setting process and consequently is particularly insightfull for the whole problematics understanding and exploration.

To deal with resource substitution synergies we will consider the following elements. 2-types of decision variables are at stake, the "strategic" and the "operational" ones. Strategic refers to commitment decision while the operational refers to the exploitation phase.

In the operational case we retain the demand orders and supply decisions. In fact the potential demand and supplies would evolve regarding deposits and needs as well as qualitative requirements.

Importantly, we consider that the latter is given (exogenous) and fixed in procedures and technical specifications of the exchange because it consist in waste streams disposal solution.

Thus the quality issues do affect the potential for profitability but not its execution. The uncertainties are represented by scenarii (Figure 3.7) on the residual key parameters (Resource deposits-R or Needs-N on the quantitative side and either prices or unit costs differences) each of them beeing assigned a probability of realization. We thus can build archetypal operational scenarii coming from:

- Resource-Needs mismatch: exogenous
- Demand order: endogenous
- "Waste" supply decision: endogenous (assumed as exogenous)

In case we would have assumed flexible substitution resource supply function it could have also been supply driven but holding this assumption, exchanges are demand driven.

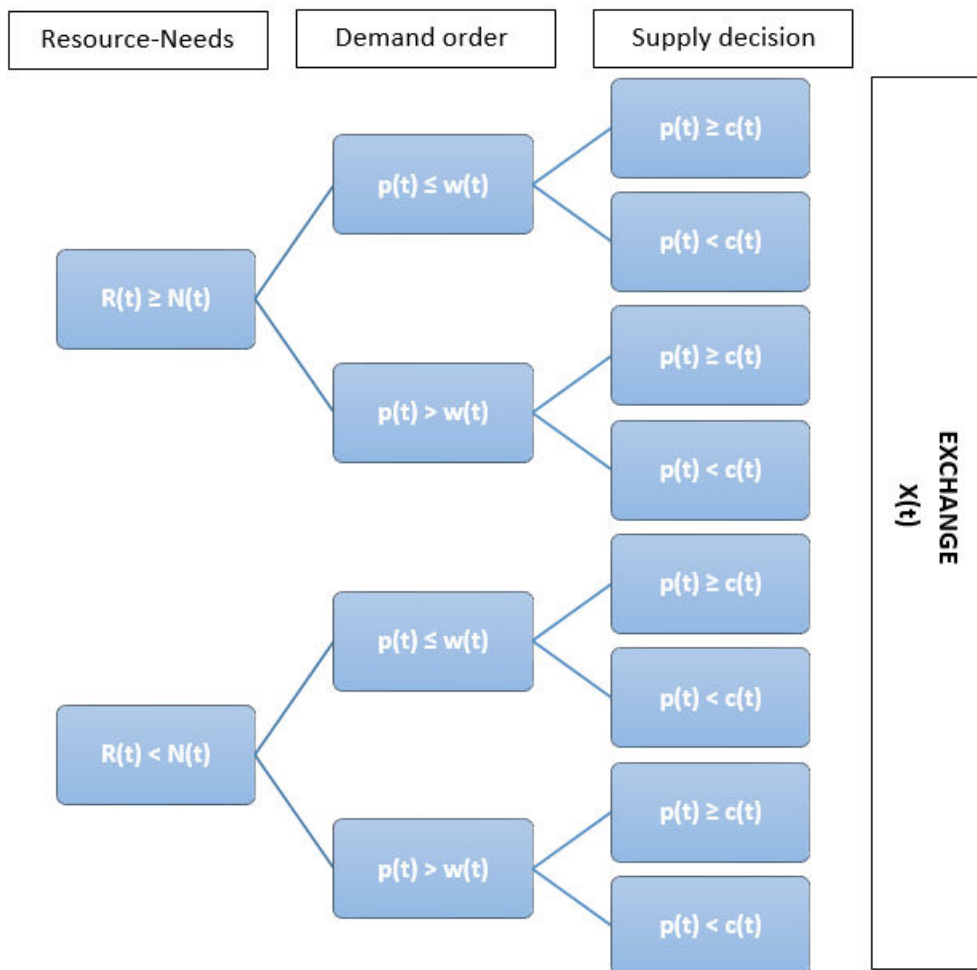


Figure 3.7: Resource substitution: Generic Scenarii

Important patterns for resource substitution

Two important dimensions associated with the transaction are at stake when dealing with resource substitution. First, technical aspects characterizing

substitution resource supply flows and downstream uses patterns since it affects "local" behavior of actors depending on the periodic parameters. Second the statistical information quality which globally impact the way to coordinate over the exchange horizon.

Transaction key technical patterns

Load profiles congruence

The very first pattern to investigate when dealing with resource substitution synergies is the potential volume of exchange sizing from the study of buyer's and supplier's load profiles that is the fine grained timing of resource needs and waste/excess energy supply. The load profiles are induced by core processes activity cycles in different periods of a day, a week a month or a year (and every intermediate split of a given operating horizon). From the analysis of load profiles congruence (taking into account optimal inventory policies options) the annual (or monthly or other) volume of exchange achievable is defined. This "net" volume is the true exchange potential of the transaction. The nominal values obtained can then be affected by persistent activity level increase or decrease (or shut-down) due to sectoral economic fluctuations. Such long term fluctuations do represent a risk in industrial symbioses.

Demand flexibility

The second is "Demand flexibility degree" which affects the technical ability for the downstream user to switch from one input mix to another.

We assume that there exist 3 kind of inputs:

the standard input, the substitution resource and the back-up solution.

The degree of demand flexibility is associated with the production technology of the buyer.

This technical feature is of first importance in substitution synergies since it delineates the ability of her to change its input mix at each time period in function of price differences so as to minimize her cost at each period t .

Flexibility can be represented by the elasticity of substitution of the isoquantity curves for a given level of output following microeconomic theory.

We thus need to identify how does the client firm would respond to a change in the relative marginal prices of the standard input and the substitution resource. For simplicity we will assume that the buyer technology exhibits one of those 2 structures.

- Full flexibility (low dependency): standard and S.R are perfect substitutes.
- Rigid (high dependency): Buyer can only use S.R and in case of shortage she might use back-up solution.

Supply flexibility

Regarding the supply of substitution resource we must investigate the impact of some key elements related to process conduct.

1) Storable vs non-storable:

Storability can mitigate part of local mismatches (load profiles) but not long term activity level evolutions. Storability is not allowed for a wide range of S.R in IS (energy, utilities or poor-quality perishable by-products).

2) Degree of flowrate control:

If the flowrate can be controlled, waste producer can switch for one elimination solution to another in the short run or not. Moreover this possibility might induce different costs.

As stated above, since we are in an industrial symbiosis context we will assume that supply is rigid meaning that the waste destination is either to the client firm or the standard treatment solution in case no contract is signed.

Statistical information

Index/ standard price congruence

A last important feature of such transactions is the existence of an objective "third party" commodity or price index that is correlated with the unit value or unit cost associated with the substitution resource flow.

Those external references can be issued from baseline raw inputs markets or former contracts such as chemical products markets, natural resources indexes (metals, gas, oil), electricity markets or labor costs.

This information allows to evaluate if the cycles between the willingness-to-pay (w) and the total unit cost of the substitution resource (c) will coincide or not in order to have an (ex-ante) evaluation of the intrinsic value of the exchanges over the planning horizon.

Nevertheless, depending on the complexity of the resource exchanged and the resource/service substituted such an information will be contained in different supports:

a) A statistical model of w and c exist,

For w , In case the resource substituted is a raw resource characterized by few conversion/mixing steps (electricity, gas, oil, wood...) indexes might exist and the statistical model can be based on objective external references. Regarding c , the cost breakdown structure should be detailed and the elements for which a reference exists listed. If the resulting cost model can be statistically related to existing indexes, information is gathered.

b) A statistical model exist for w or c does not exist,

In that case the client organization do not have direct access to the statistical model of former standard supplier cost information. This is the case for more complex product or if the service was provided using an undefined mix of resources and processes. Contractors cannot identify all the deep drivers

because they were not displayed by standard suppliers. Look at the standard price indexation schemes available in former long term contracts or try to establish a statistical model of the prices paid with the available indexes to re-estimate the model.

The treatment of statistical "objective" information is a key element to define properly the cost target to consider before negotiating exchange prices in contracts. It is a prerequisite to evaluate the value of the synergies. Moreover the existence of an objective "third party" can be leveraged as a suited coordination tool within contracts.

3.2.4 Analysis-contractual design guidelines

In order to analyze value generation and appropriation we focus on transactions and more especially on tariffication issues. Indeed tariffication associates key dimensions for economic analysis of symbioses. Items of various natures like resources quantities, capacities and quality requirements do translate into an economic criteria. For each actors, preferences over the transaction options are represented by value flows over the horizon.

At this point we must indicate that the aim of our work is to provide a structured framework to establish contractual designs but not an analytical economic model per-se. Such additional investigations based on our framework are proposed as extensions for further economic research in the field.

Cases definition: designs drivers

As we acknowledged the content of a contract will be affected by contextual patterns characterizing the transaction at stake when dealing with resource substitution.

Using our demand flexibility patterns, cost structures and statistical links we

then define archetypes.

Nature / time frame	Global	Period	infra-period
Endogenous	Capacity-flexibility	exchanged volume	supply-demand
Exogenous	cost function	load profiles	resource-needs
Contractual	Commitment	Warranties	Prices

Table 3.2: Transaction structuration for resource substitution

Achieving Target value: Pricing performances and warranties

A first step in contracting over value is to define the anticipated failures that can be harmful for the global satisfaction of the buyer (B) and the seller (S). The basic economics of the resource substitution synergy is depicted as follows. To be implemented the resource substitution should be profitable for both the buyer and the seller in expectation that is:

$$\text{for } i \in (B, S), H \cdot \mathbb{E}(V_i(t)) \geq (1 + r_i) \cdot I_i$$

In less aggregated terms,

$$\text{for } i \in (B, S), \sum_{n=1}^{H/h} h \cdot \mathbb{E}(V_i(n)) \geq (1 + r_i) \cdot I_i$$

With:

$$V_B(n) = \sum_{t=h(n-1)}^{hn} V_B(t) = \sum_{t=h(n-1)}^{hn} \min\{S(t), D(t)\} \cdot (w(t) - p(t))$$

$$V_S(n) = \sum_{t=h(n-1)}^{hn} V_S(t) = \sum_{t=h(n-1)}^{hn} \min\{S(t), D(t)\} \cdot (p(t) - c(t))$$

with: H the project time horizon, n the number of contractual period of duration h and V the value achieved.

I is the investment cost and r the minimal return on investment required.

Payment schedules represented by the equations hereabove pertains to the pay-per-unit with wholesale price contract.

The key part in buyer-seller models is the definition (or bargaining) of prices.

Nevertheless a simple widely studied pay-per-unit contract with linear tariff scheme is a particular case of supply contract.

For instance the use of (call) Options contracts allow to give the supplier a warranty regarding payments. Indeed the option price is already paid before buying decisions (dependant upon the difference between the strike price and the standard resource price).

In the following we will propose contract designs along the wholesale price of course but also warranties and penalties pricing in order to improve (demand) flexibility while sharing risks induced by this flexibility. In real contexts we must specify the causes and consequences of having those configuration to specify contractual devices. Here we restrict our attention to the abovementioned information. The risk sharing is then related to the component of scenarii that is imbalances compared to the nominal target value.

Contractual provisions and forms are then of first importance.

Informational coordination devices in contracts

Contract provisions adaptation is possible in multi-period settings. Adaptations must be done on the basis of informations from the environment of the transaction. From the transaction's global perspective the planning horizon of contract exploitation is given according to buyer and seller satisfaction.

As we explained, this global horizon might be splitted in subsets of sub-horizons composed of infra-periods. Those infra-periods can be defined as a year or other infra-periodic scales (month, day, hour, second...). It is worth noting that each period can be splitted further in infra period (self-similarly). This decomposition allows to structure the information processing for the symbiosis in function. Depending on sub-horizon patterns regarding either exogenous variations or endogenous (decision variables) choices that have to

be done by actors within each time frame considering available information.

Information adaptation

Quantity Flexibility terms are used in supply contracts for highly production rates dependant and volatile demand (or deposit supply).

Price adjustments based on indexation schemes can be associated with both quantity flexible or fixed quantity provisions.

In the former they will incentivize the buyer to accept more regularly the supplies in the infra-periods of the horizon ex-post. Form this regularity global commitment (ex-ante) is possible. In the latter where no further choice have to be made (rigid demand) it provides an incentive to commit to the contract ex-ante. This ensures a (better) match for both suppliers side and demand side along the transactions horizon. The price should follow the costs increases and the best alternative price moves. A challenge is to identify which is this "best" alternative to consider in the indexation scheme. Moreover an accurate indexation on costs would reveal private informations on processes and technologies so that firms might use imperfect indexation formulas to fuzz-up the signal.

Pricing substitution resource thus depends on an 2-sided indexation scheme that allow to follow-up value changes dynamically in order to adapt to economic environment changes.

The substitution resource unit price $p(t)$ upper bound and lower bound are given by the indexation equations:

$$\begin{aligned} \text{Cost-plus: } \underline{p}(t) &= \underline{\pi}_S + \sum_e s_e \cdot c_e(t) \\ \text{Price-cap: } \bar{p}(t) &= \sum_v s_v \cdot w_v(t) - \underline{\pi}_B \end{aligned}$$

where: $\underline{\pi}$ is the minimal per-unit profit (resp.cost savings) targeted by the seller (resp. the buyer). e is the set of cost drivers and v the set of value

drivers and s the respective technical coefficients for each driver.

The bargaining of the unit prices then determines simultaneously the respective value of π_i under the constraint that in expectation π_S and π_B be such that the symbiosis is mutually worthwhile. This is given by the equation:

$$\sum_v s_v \cdot \mathbb{E}(w_v(t)) - \underline{\pi}_B \geq \mathbb{E}(p(t)) \geq \sum_e s_e \cdot \mathbb{E}(c_e(t)) + \underline{\pi}_S$$

In case ex-ante, on the basis of the available information on cost breakdown structure and willingness to pay model of the buyer this equation does not hold, the resource substitution will not be implemented. While the prices and costs can be indexed on external references, the "volume" part of the periodic value streams V required to achieve profitability is at risk but on a different manner. Intrinsically associated with symbiosis involved individual actors characteristics (plant situation in a network, sectoral fluctuations, core processes changes) the risks must be managed with different contractual terms. In the following we propose contractual devices tailored to align expectations regarding the appropriate "volume" of transactions.

Flexibility in contracts: quantity based payment schedules

In the following we will introduce the design of additional provisions that are warranties and penalties and investigate their influence on the risk sharing properties of contracts.

Thus following generic contract architecture we proposed we will investigate the value exchange drivers behind contractual devices specifications and especially performance and warranties pricing provisions.

To understand this we must target whether it comes from exogenous failure or behavior (endogenous). In the first case warranties will not be induced by incentives rather by reparation. Within a given contract type provisions can differ. Provisions can target the *occurrence* of a risk or its *consequences*.

Warranties/penalites

Minimum bill schemes:

Relative to a sub-horizon n of length h . The value required to achieve the seller's objectives might not be too far from the actual realized value in this sub-horizon. To mitigate this risk the buyer will act on the demand volume $D(n)$ and thus require minimum total volume warranties over each sub-horizons n . Using such a provision the buyer limits the risk arising from resource needs cutoffs (due to economic conditions) or from resource mix arbitrages that are thus dampened by the penalty.

$$\forall n, \sum_{t=h(n-1)}^{hn} D(t) \geq \underline{D}$$

Minimum bill Penalties:

If the minimum bill constraint is not respected, it will trigger a penalty scheme. Such a penalty scheme will be defined by the minimum bill distance (realized vs contracted), proportion of this distance γ , payment scheme (lump sum or unit-penalty). A penalty cap can be applied to limit the penalty to be paid at a maximum. Too high penalties would indeed overvalue the states in which it is triggered for the seller and associate a too harmful outcome for the buyer in those scenarios. The consequence is a risk of imbalance detrimental to the mutual commitment since the supplier doesn't need such a high payment while such outcome might mitigate client's willingness to commit.

$$P_{\gamma}(n) = \frac{1}{h} \sum_{t=h(n-1)}^{hn} p(t) \cdot \gamma \cdot \max\{\underline{D} - D(n), 0\}$$

Minimum Supply warranties:

The structuration is symmetric. Supply warranty is defined by a certain given level (over a sub-horizon). The Design should define it as a warranty over the effective demand orders formulated by the client within a given sub-horizon.

Indeed the supplier would not be charged a penalty fee in case demand was lower than the agreed upon warranty level. Moreover this warranty might be bounded above as a "capacity" constraint over each sub-horizon n (\bar{S}_n). The upperbound is determined by the study of supplier's load-profile over n .

$$\forall n, \alpha \cdot D(n) \leq S(n) \leq \bar{S}_n$$

Shortage penalties:

Following the definition of the supply warranty the penalty should be envisaged as a "shortage" penalty. In case the shortage would be induced by a deliberate undersupply decision by the seller it would incentivize him to supply the demand (at least partially). If the shortage comes from an exogenous lack of substitution resource it would compensate the client for the gap between the ordered quantity and the effectively supplied one. This compensation is then calculated on the basis of the back-up cost solution (B) to be used or the cost of not produce at all (lost sales). Depending on cost differences between the back-up solution, the standard input and the substitution resource supplies this mechanism can notably induce efficiency.

$$P_\alpha(n) = \begin{cases} \frac{1}{h} \sum_{t=h(n-1)}^{hn} B(t) \cdot (\alpha \cdot D(n) - S(n)) & , S(n) \leq \alpha \cdot D(n) \leq \bar{S}_n \\ 0 & otherwise \end{cases}$$

Those provisions are included into the contract to mitigate transaction volume related risks and complement the indexation pricing scheme towards mutual commitment. Moreover in real business contexts the flexibility allowed using such schemes gives room for structured negotiation and adequate degrees of freedom in the operational phase notably for the flexible buyer who could be reluctant to enter a too rigid contract. In addition appropriate pricing and the associated quantity flexibility and penalties do "smooth" the impact of periods characterized by persistent bad outcomes which is of

first importance for practitioners regarding their financial statements and managerial concerns.

Renegotiation: conditional vs unplanned

Renegotiation of contractual parameters is allowed during the planning horizon H . Renegotiation will be both state dependant (exogenous parameters) and arrangement dependant (voluntary) since both do have influence on the renegotiation's bargaining sets (credible outside options and residual ex-post value). Enforcability must moreover be studied along two ways since part of outside options are directly enforceable by courts and other will be self-sustained by relational arguments in multi-period settings or considering renegotiation as sustaining transaction whenever it implies efficient ex-post bargaining. Renegotiation consists in the same process as the one we are describing but given different initial conditions and a limited scope of application (convex sub-sets of H). Renegotiation can be worthwhile if it allow to coordinate better the buyer and seller who learn more accurate statistical information along the contract life cycle and the status of the transaction (realized payoffs and distance to objectives). A risk in renegotiation is to harm one of the parties in case the economic environment allow one or the other to hold-up the other. This problem have been extensively studied in the economic literature and renegotiation can then be an issue regarding commitment. In our context (resource substitution) the high degree of mutual asset specificity forgoes credible outside options for each of the partners. As a consequence renegotiation is more considered as an additional flexibility option rather than a "Damocles sword" pending above contractors head.

3.3 Synthesis and recommendations

We proposed a framework to structure the contracting process as well as the contracts themselves for resource substitution synergies. Due to specific features of such exchanges and the high degree of asset specificity and products customization needs we argue that complex contracts should be written beforehand in order to make buyer and seller commit to the transaction.

We then proposed a generic contract architecture to provide the basic elements that should be considered altogether when contracting over such a transaction.

First, the buyer and the seller must clearly determine who is their co-contractor and if there exist third parties with which supplemental contract should be entered to achieve resource substitution. Then a contract object must delineate the performance that will be priced with targeted quality requirements contained in the bill-of-specifications. The payment model retained is a pay-per-unit (either of service or for product) depending on the existence of a property transfer. Property transfer is suitable whenever some of the conversions operations have to be made at the client's discretion. The unitization is useful to build the cost breakdown structure of the resource as well as the value model (what resource it substitutes).

After having properly define the contract object and the bill-of-specification and chosen the transfer formula the contract must specify the pricing formulas according to a pay-per-unit pricing scheme. At this level, as we acknowledge, the unit price must be defined using two bounds that are respectively the minimum unit gain required by the buyer and the minimum gain needed by the buyer to achieve (in expectation) their profitability objectives. Such bounds are also determined by the resource cost drivers and their respective shares (lower bound) and the value drivers that is the mix of re-

sources substituted. Pricing depends upon variability and need for flexibility. The more it follows production rates the more flexible and thus uncertain are the outcomes. If the demand elasticity to production rates is low then payments can be periodic and stable.

It is important to build consistent price-index for a variety of baseline cost or make it available. In order to define this unit price, information must be gathered either from statistical sources on commodities or other materials prices or from contractual provisions used by standard suppliers so as to reconstruct the price and gain statistical information to evaluate whether or not the average unit price in the contract can be acceptable by the two contractors. Once this price is determined (or rather the indexation scheme is accepted by both parties) the contract should set-up warranties to manage quantity related risks. Indeed cost and prices are uncertain but they do not belong to each actor intrinsic characteristics and behavior. It is for this reason that external information must be gathered, processed and entered into the contract. Regarding quantity issues (the second arm of value creation) contractual warranties and associated penalties must be contracted upon by actors. Once again we propose a 2-sided warranty system comprising 2 minimum level provisions and penalties compensating in case of infringement. The penalties are based on the nominal (average) level of value needed over a sub-horizon to match with the global objective satisfaction criterion. Proposed contract thus includes minimum bill provisions on a specified sub-horizons of length "h". This minimum bill is a part of the nominal average exchange level needed to ensure break-even for the seller (and the buyer). The more the flexibility is increased "h" the more the minimum-bill would be higher. The size of this sub horizon over which quantities are subject to warranties will depend on the flexibility level of the demand (the buyer) which

is also an important parameter to be investigated during contracting process. The more the time-window will be long that more the penalty should be high to compensate for an higher risk of too low exchange. Sub-horizon minimum bill to allow for flexibility but ensures partly the demand risks and supply failures. The penalty choice gives global incentives over the sub-horizon and thus smoothes outcomes locally as well as globally. For exogenous activity decrease inducing low demand the minium bill acts as an insurance mechanism at the scenario level it compensates between states within a "scenario" since profitable conditions overbalance non-profitable ones.

Compensation also plays "across scenarii" because some scenarii exhibit high frequency and/or high impact of profitable states whether other are composed of frequent or very harmful states.

In addition to those risk sharing features a contract designed along those dimensions seems worthwhile in practice since it is simple, clearly related to each actor objectives, allow for operational flexibility and proposes locally balanced outcomes that is important for managers because it ease the financial stability and equilibria of cashflows (or savings) generated by the resource substitution synergy.

Chapter 4

Economic modelling of Infrastructure sharing synergies

4.1 Economics of infrastructure sharing synergies: basics derived from the literature

In this chapter we will focus on the synergies stemming from sharing practices that is infrastructure/service sharing synergies. As we have seen this type of synergy is based on the common access, use, and sharing of means ensuring a performance valued by the participating actors. Infrastructure sharing thus consists in the use of collective capacities or resources to satisfy individual needs. As depicted in our taxonomy, the sharing practices involves mainly *infrastructures, services, resources* (financial or material) and *information* (organisation). Regarding infrastructures their functions range from production plants, to treatment units and also transportation and storage (logistics). Infrastructure sharing can be viewed as a common use of an infrastructure capacity and is closely related to the access to an associated

service or function¹. Moreover it is important to acknowledge whether cooperation includes the design phase of the infrastructure setting before its construction or just an extension (less degrees of freedom) or just the access to a pre-existing one. At this point it is important to note that infrastructure sharing synergy supposes the comparison with an alternative option to be meaningful that is the stand-alone case. In consequence it can be envisaged as a substitution process. In the context of IS the term "substitution" will be used in the context of synergies based on exchanges of flows of materials and energy. The cost-model and then the potential synergies achievable highly differ depending on the phases in which cooperation occurs since it affects the cost drivers at stake. In "downstream" phases (infrastructure use) few cost drivers can be efficiently managed since the capacity is fixed.

On the contrary during the design and construction phases the total costs can be reduced due to the technical effects associated with the concavity of the capacity investment cost function and sub-modularity of components in the infrastructure architecture. Indeed this pattern is demonstrated in the statistical studies at the root of capacity-based capital costing models developed in the process industry literature (Couper et al., 2008; Chauvel et al., 2001). Additional strategic effects can also allow for cost reductions from the improvement of bargaining power during negotiations with contractors when pooling capacity needs thus project size.

Due to those combined economies of scale the global cost is reduced compared to the alternative scenario in which each actor would rather design and construct its own infrastructure. In addition, since the cost driver is the actual needed capacity for the group of actors, acting on this global capacity

¹Infrastructure sharing can include the sharing of a residual value of the infrastructure if we consider common ownership rights allocation.

Detailed	$I(K) = \sum_1^e a_e k_e^{\beta_e} + \text{indirect}$	$\forall e \in E, \beta_e < 1$
Semi-detailed	$I(K) = (1 + \sum_1^c b_c) \sum_1^p a_p k_p^{\beta_p}$	$\forall p \in P, \beta_p < 1$
Global	$I(K) = \alpha K^\beta$	$\alpha > 0, \beta < 1$

Table 4.1: Cost estimation formulas

need itself can further improve the situation. Indeed the synergy is further reinforced if the global capacity need can be set at a lower level. At this point individual actor load-profiles drive the peak capacity needed and thus the capacity level to be set. The more the load-profiles of participants are complementary (in the required capacity sense) the less the required capacity is high. In the extreme case in which all individual peak loads would coincide infrastructure sharing would still be synergistic due to the concavity of the investment cost function.

Formalisation: total cost of investments estimation types (from Couper et al. (2008) and Chauvel et al. (2001)).

Cost estimations formulas are more or less detailed in function of the available information on infrastructure characteristics. Detailed methods use the sum of each of equipments' (e) costs derived from their individual capacities (k) required to achieve a global capacity of K to perform the evaluation. Semi-detailed methods use only the set of principal equipments (p) in addition to auxiliary costs (c). Global methods used in pre-project evaluations use rather the installation capacity K . Each of the equipments, principal equipments and capacity do have an associated scaling factor linking the size of the required equipment (or infrastructure) to the required capacity (the β exponents). In the case of global infrastructure capacity cost evaluations this exponent is lower than 1 meaning that infrastructure capacity costs exhibit economies of scale.

Infrastructure/service sharing synergies:

In this type of strategy synergies are achieved according to budget savings on service or equipment use expenses. Budget can be reduced by leveraging technical (or commercial) economies of scale (rebates) by pooling capacity needs ($K(U)$) and sharing the resulting global expense ($C(K)$) among users so that to cut-down each actor standalone costs (c).

In the specific case of sharing synergies, Gains from infrastructure sharing

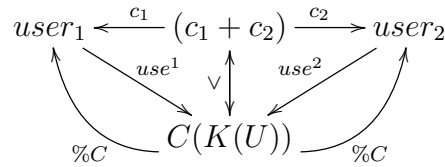


Figure 4.1: Infrastructure sharing value mapping

and resource pooling strategies can be analysed using coalitional game theory using submodular cost functions in a first category of models. Further investigations can consider congestion effects sized by participants profiles and related to the decided capacity level must be considered. Congestion effects may induce non-monotonicity in the gains so that the grand coalition may not be nor optimal nor stable.

Some cases of infrastructure sharing practices

We briefly introduce classical forms of infrastructure sharing practices in the following section and describe the various economic problems raised and the way involved actors can interact.

In the case of Infrastructure setting and operation for common utility supply: Practical cases involves heat (steam) network, water network, common power and utilities supply in industrial parks.

A central question is what matching configuration can emerge considering individual actors autonomy and collective decision making needs.

The industrial problem can be formulated as a set of firms can supply an input to a utility generator.

and/or a set of firms can use the provided utility by connecting to the supply system and enter into transaction with the system operator.

In such cases we can face different organizational alternatives. In one case, the system is operated by a service provider who can contract with the two sides of the market (resource suppliers and utility users).

Another possibility is that the system is owned by the suppliers who decide what subset of clients should be served and how the surplus must be shared depending on their contributions.

Similarly, the clients (users) owns the network and decide what suppliers to select and how the cost have to be shared.

We can also consider mixed forms in which subsets of clients (suppliers) can pool their demands (supplies) and decide which subset of suppliers (clients) have to be selected.

Regarding energy supply plants, many IS are based on the furniture of energy from CHP plants, incinerators exhaust heat or Biogaz conversion plants.

In those cases configurations can consist in 1 (a set of) substitution input provider can supplies a producing station (as energy or commodity plant).

The input provider also consumes the utility. A second (set of) firm just consumes the commodity but do not deliver any substitution input to the plant. Depending on market conditions and ownership structure(including third-party owned plant) an economic puzzle is to determine how does the system surplus is generated and split among these firms.

This case in encountered in cases where a CHP plant or incinerator provides

a energetic service to several actors. Some of those clients may give an input to be used in the plant to produce energy. In addition part of the suppliers can be serviced back by the plant. A set of clients do not supply any input but consumes the plant output. Such systems can be organized as follows. The plant is owned by the substitution input supplier who have to decide whether or not contracting with the client firms. In another form, the plant is owned by the client firm who can contract with the supplier to source inputs and/or to sell utility. Else, the plant is owned by a third-party (utility provider) who can contract with the input supplier and the client. Also, the plant is owned by the two firms who need to design a rule to split the costs on the basis of their respective contributions.

The issue of competition among suppliers whenever the system can be feed by substituable supplies (of the same nature or for same use) is an economic question. In case of competition what endogenous structures might emerge and what is the resulting efficiency loss compared with centralized resource allocation ?

A set of eco-industrial suppliers and a set of eco-industrial clients are here involved. Substitution Inputs provided can be either complements (case1) or substitutes (case 2) for a given client.

For a given producer its inputs can be sold to a subset of clients leading to an arbitration on which clients to be served (possibly using discriminatory practices and facing competition from other eco-industrial input providers). Depending on the economic environment (Fixed and variable costs, market references, technical patterns as distance, demand profile or process compatibility) and strategic positionning assumptions different configurations can emerge.

Those configurations can be different from the optimal centralized solution

due to strategic gaming stemming from market structures. EIP welfare can be affected by such equilibria.

Transactional linkages can have several forms. Every supplier can negotiate with each buyer to establish a contract for the input. If present, a broker purchases inputs from the upstream enterprises and sell it to the client firms. The broker objective is either to maximize social surplus (social planner) or its own profit (selfish middleman). In an other possibility, the downstream enterprises might pool their demand and contract with the suppliers for input provision. Decision to contract is taken according agreed-upon rules set by the clients themselves. Also, the input providers can pool their supplies and contract with the clients. Common decision is taken according to agreed upon set of rules.

The examples described above shows the various configurations we can face in practice in the case of infrastructure sharing synergies. In the following we will build a generic instance in order to analyse simultaneously the foundations and drivers of the capacity setting decision and capacity access pricing in infrastructure sharing synergies accounting for the heterogeneity of actors roles in such practices.

4.2 Economic models of infrastructure sharing

4.2.1 General model: elements and notations

In order to investigate the decision of actors to share a common infrastructure we propose economic models proposed in recent own contributions in this section(Molinier and Da Costa, in Press; Molinier, 2018a,b). Our models will consider the value of sharing an infrastructure for many actors interacting

over such a symbiosis and derive conditions leading to implement such a practice.

Hereafter we define the set of actors to be considered and their status, the set of parameters and decision variables at stake when analysing infrastructure sharing synergies.

Static analysis

As we mentioned earlier, infrastructure sharing synergies are related to the collective use of a shared capacity level K .

The capacity setting has an investment cost driven by the capacity level $I(K)$ of the form $I(K) = (1 + \alpha)K^\beta$ with $\alpha > 0$ and $\beta \in [0, 1]$.

Investment cost is thus defined by a scaling factor β linking the technical capacity need with the global scale of equipments needed and a cost factor $(1 + \alpha)$ linking the equipments size required to a global infrastructure cost level. This formulation indeed follows the structure of global methods in the cost engineering literature. Following this higher α model higher total cost of investments for a given equipment level. More importantly β represents the degree of economies of scale exhibited by the infrastructure. For $\beta = 1$ infrastructure duplication is equivalent to infrastructure capacity duplication meaning that the infrastructure cost do not exhibit economies of scale. If β is lower than 1 then economies of scale gives room for profitable capacity expansion over infrastructure duplication. For this reason β will be a key parameter regarding infrastructure sharing synergies.

The way the capacity level is used depends on the requirements level (individual quantities) q_i needed by each (potentially) interested actors $i \in A$. In a first step, for simplicity and to focus on cost-cutting effects we will assume that all quantities required by users sum-up to the sum of quantities required

meaning that the load profiles are themselves not synergistic. In case the requirements would be higher than the capacity level which has been set, a back-up cost \mathbb{B} is incurred to fill the capacity gap.

We assume that the back-up cost is linear in the capacity gap so that the cost is of the form $B \cdot \text{Max}\{\sum_i q_i - K, 0\}$ where B is the unit back-up cost. We assume that once set-up, the infrastructure capacity can be used at a 0 marginal cost so that it is always more costly to use the back-up solution than the right infrastructure capacity level.

Considering this assumption we have that $\forall q > 0, B \cdot q > I(q)$.

Thus the efficient capacity to set will be equal to the sum of required capacities $K = \sum_i q_i$. In that context, following our assumptions we can show that the core of the cost sharing game associated to the sharing symbiosis is non-empty due to the "snowball effect" whenever $\beta < 1$. In other words it is optimal for any individual actor i to join the grand coalition of size $\text{Card}\{A\}$. Indeed their individual willingness-to-pay (WTP) to access the infrastructure (and use it) is equal to their standalone cost $I(q_i)$ so that any Tariff $T_i \leq I(q_i)$ will be accepted by actor i . Since whatever $a \subset A$, $\sum_{i \in a} I(q_i) > I(\sum_{i \in a} q_i)$ we can always find imputations of the form $T_{i \in a}(K)$ such that $T_{i \in a}(K) \leq I(q_i)$ and $\sum_{i \in a} T_{i \in a}(K) = I(\sum_{i \in a} q_i)$.

The issue of dynamics

So far we only considered certainty about any parameters in the model. One particular feature of sharing synergies is that it can be leveraged dynamically by purposely setting higher capacity level to attract future partners that will use the infrastructure. Such a puzzle have been notably faced and raised by many practitionners within EIP we interviewed and visited during the first year on investigations. Moreover since considered infrastructures

generally have life spans of 20 years or more it is valuable to broaden the economic problem of sharing synergies integrating the potential entry of future users. In consequence, the future requirements of new entrants are not known beforehand so that the capacity level choice have to be made considering also uncertain additional requirements. Extending the reasoning to dynamic contexts requires to split the set of actors in 2 subsets, a first subset A (the tenants) of actors (or a service provider who operates a capacity) with known and certain requirements level at the time to choose the irreversible capacity level and a second subset E of actors whose capacity requirement are uncertain at the time of capacity investment (the entrants). The dynamics comes from uncertainty resolution after the irreversible investment decision have been made ex-ante. The strategic decision variable of the tenants is thus the over-capacity level (k) to set ex-ante anticipating the entry of future partners looking for attractive infrastructure access and use ex-post.

For simplicity we will assume that the total additional requirement level of entrants $e(x)$ ranges from 0 (no-entry) to 1 (maximal potential requirement) that is $x \in [0, 1]$. A difference when it comes to reaching an agreement on access price with new entrants is that the achievable value is constrained by the investment decision made in the first period. After investment in $K + k$ had occurred (and the tenants have paid the corresponding amount) an entrant addresses a demand for the access to the infrastructure available capacity k . Access is conditional upon a payment $T_e(k)$ that the entrant should transfer to the tenants. This access price is set by private negotiations between the entrant and the allied tenants who own the infrastructure. As a consequence we must consider in our dynamic model the ex-post entrant's rationality constraint which is given by: $T_e(k) \leq I(x) - B \cdot \max\{x - k, 0\}$.

Where $T_e(k)$ is the tariff proposed by the tenants to the entrant. Assum-

ing that if the entrant decides to connect to the tenants' infrastructure, he cannot build its own capacity and must use the back-up solution in case of capacity shortage. The entrant's WTP is bounded by its standalone cost $I(x)$ if $k \geq x$. In case $k < x$ the entrant's WTP is decreased by the back-up costs for compensating the capacity gap during exploitation $B \cdot (x - k)$. In practice if this back-up cost is incurred by the tenants or the service provider which operates the infrastructure this cost will be transferred to the entrant in the exploitation phase so that the reasoning is symmetric and the consequence is the same.

Rationally the entrant will be willing to accept the offer if he gets a cost advantage from it. Thus the payment made to the tenants and for the back-up costs must not exceed the standalone cost. Otherwise the entrant would prefer to build his own infrastructure. To close the bargaining set associated with this private negotiation game, we must derive the tenants rationality constraint. Actually this constraint is easy to derive since it corresponds to a non-negative tariff offer. Indeed after the entrant's requirement (x) is known tenants must earn a non-negative revenue from the offer they make to the entrant so that this constraint is simply stated as $T_e(k) \geq 0$. Trade will occur in period 2 if and only if the ex-post bargaining set non-emptiness condition is satisfied, that is $0 \leq T_e(k) \leq I(x) - B \cdot \text{Max}\{x - k, 0\}$. In the following sections we will investigate the conditions influencing the investment behavior of tenants and entrants access choices regarding the implementation (or not) of infrastructure sharing synergies. To do so we will develop different economic models integrating the parameters, functions and behavioral considerations (actors objectives and constraints) described above. Results will be detailed for 2 different specifications regarding the attitudes towards uncertainty for the tenants who should invest (or not) in additional capacity levels (k) so as to

benefit from economies of scale in an farsighted industrial symbiosis strategic perspective. In a first formulation we use the Laplace criterion whose basement is grounded on expected value framework (compensation between states associated payoffs). In a second we depart from expected value based criteria and adopt a robust optimization perspective using a min-max regret criterion which is well suited to address our optimization problem. Extensions are then proposed for each specification including additional parameters in the baseline models. In the model extensions we will first consider the impact of time value of money on capacity choices, the influence of different bargaining power repartition between the tenants and the entrant. We will also extend the first formulation by considering uncertainty on load profiles congruence degree. Theoretical results are derived regarding the properties of the objective functions at stake and the conditions for their optimization as well as the form of their solutions. When needed and permitted by the theoretical conditions, the optimization programs numerical resolution and other various simulations performed in those sections have been done using Python programming optimization environment (SciPy Optimize). In a last section we start from the cooperative context we implicitly assumed so far and propose investigations towards the capacity choices of tenants whenever they face competition from the other to attract non-cooperatively the potential entrants.

4.2.2 Capacity oversizing under uncertainty-Laplace criterion

Baseline model

Capacity choices are at the core of infrastructure sharing synergies. In this model we analyze the capacity investment decision of tenants in a dynamic context considering the value of potential entry of new users. To build our economic model we will use the notations and model elements described in the previous section. The question we address with our model could be stated as "In which conditions tenants in an EIP will purposely set over-capacities to leverage future infrastructure synergies opportunities?".

We thus propose a model focusing on the overinvestment decision of tenants that is on the decision variable k . More precisely we will describe the choices made in different business environments that is the behavior of the optimal over-capacity chosen by the tenants k^* depending on the degree of economies of scale, the back-up cost and the tenants' size ($k^*(K, B, \beta)$).

Laplace Criterion:

In order to model the attitude of tenants towards the uncertainty over the entrants requirements level x we use an optimization program for tenant's choice based on expected profit maximization with uniformly distributed entrant's requirements.

This formulation is called the Laplace Criterion since it uses as a distribution for the uncertain parameter (here x) the probability density function with the lowest informational content: the uniform distribution.

Following this line of inquiry we consider that $x \sim \mathbb{U}_{[0,1]}$.

Behavioral considerations:

Tenants seek to maximize the expected profit they will earn from the overca-

capacity k . Before uncertainty is resolved about the entrant's requirement level the tenants should decide the level of overcapacity they will set balancing the (deterministic) investment cost increment to be incurred with the expected payment they anticipate from the entrant ($\mathbb{E}(T_e(k))$).

It follows that the expected profit for the tenants is:

$$\mathbb{E}(T_e(k)) - [I(K + k) - I(K)] = \mathbb{E}(I(x)) + I(K) - [\mathbb{E}(\mathbb{B}(k)) + I(K + k)]$$

From this expression we can derive the tenant's ex-ante rationality constraint:

$$\begin{aligned} 0 &\leq I(K + k) - I(K) \leq \mathbb{E}(T_e(k)) \\ &\Leftrightarrow \\ I(K) + \mathbb{E}(\mathbb{B}(k)) &\leq I(K + k) + \mathbb{E}(\mathbb{B}(k)) \leq I(K) + \mathbb{E}(I(x)) \\ &\Leftrightarrow \\ I(K + k) + \mathbb{E}(\mathbb{B}(k)) &\leq I(K) + \mathbb{E}(I(x)) \end{aligned}$$

Tenants program:

Expected profit maximisation is equivalent to the minimization of the following objective function $O(k)$:

$$O(k) = \mathbb{E}(\mathbb{B}(k)) + I(K + k)$$

Thus the tenant's program is the following:

$$\begin{aligned} &\min_k \{ \mathbb{E}(\mathbb{B}(k)) + I(K + k) \} \\ \text{s.t: } &I(K + k) + \mathbb{E}(\mathbb{B}(k)) \leq I(K) + \mathbb{E}(I(x)) \\ \text{with: } &\mathbb{B}(k) + I(K + k) = (1 + \alpha)(K + k)^\beta + B \cdot \int_k^1 f(x)(x - k)dx \end{aligned}$$

Where: f is the probability density function of x (F its cdf).

The tenants' program is equivalent to a cost minimization problem with two components, a direct cost ($I(K + k)$) and an opportunity cost ($\mathbb{B}(k)$).

The form of the program faced by tenants indicates that under some circumstances (parameters values) that we will investigate hereafter, the minimal

expected cost of the sharing agreement may not generate sufficient savings regarding the global expected costs without additional capacity setting. In that case there will be no overcapacity setting ex-ante ($k^* = 0$) so that the solution of the program is given by:

$$k^* = \begin{cases} \operatorname{argmin}\{O(k)\} \\ 0 \end{cases}$$

General results:

1) Analysis of the expected back-up cost function

We have that $\mathbb{E}(\mathbb{B}(k))$ is decreasing and convex in $[0,1]$ and admits a maximum in 0 and a minimum in 1 with respectively $\mathbb{E}(\mathbb{B}(0)) = B \cdot \mu$ (where $\mu = \mathbb{E}(x)$) and $\mathbb{E}(\mathbb{B}(1)) = 0$.

Proof: $\mathbb{E}(\mathbb{B}(k))$ is decreasing and convex in $[0,1]$

$$\begin{aligned} \forall k \in [0, 1], \quad \frac{\partial \mathbb{E}(\mathbb{B})}{\partial k}(k) &= -B \cdot (1 - F(k)) \leq 0 \\ \forall k \in [0, 1], \quad \frac{\partial^2 \mathbb{E}(\mathbb{B})}{\partial k^2}(k) &= B \cdot f(k) > 0 \end{aligned}$$

2) Analysis of the objective function

A minimizer of the objective function is given by the first order condition when O is convex in k :

Proposition:

$$\forall k : kf(k)^{\frac{1}{2-\beta}} \geq (B/(1+\alpha)\beta(1-\beta))^{1/(\beta-2)} - K$$

$O(k)$ is convex and we have:

$$\operatorname{argmin}\{O(k)\} = y : \begin{cases} y(1 - F(y))^{\frac{1}{1-\beta}} &= \left(\frac{B}{(1+\alpha)\beta}\right)^{\frac{1}{\beta-1}} - K \\ yf(y) &\geq \left(\frac{B}{(1+\alpha)\beta(1-\beta)}\right)^{\frac{1}{\beta-2}} - K \end{cases}$$

Results: Laplace Criterion - Uniform distribution

From the use of the Laplace criterion to model attitude towards uncertainty

of the tenants we have the following:

The entrant's requirement is uniformly distributed on $[0, 1] : x \sim \mathbb{U}_{[0,1]}$.

As a consequence we have: $\mu = \mathbb{E}(x) = 0.5$, $F(x) = x$ and $f(x) = 1$.

Moreover from our baseline assumption on cost functions we have:

$$B \geq \left(\frac{1+\alpha}{1+\beta}\right) \cdot \frac{1}{\mu}$$

The objective function is:

$$O(k) = (1 + \alpha)(K + k)^\beta + B \cdot \left(\frac{1}{2} + \frac{k^2}{2} - k\right)$$

It follows that $\operatorname{argmin}\{O(k)\} = y$

$$\text{with } y : \begin{cases} y(1 - y)^{\frac{1}{1-\beta}} & = & \left(\frac{B}{(1+\alpha)\beta}\right)^{\frac{1}{\beta-1}} - K \\ y & \geq & \left(\frac{B}{(1+\alpha)\beta(1-\beta)}\right)^{\frac{1}{\beta-2}} - K \end{cases}$$

Uniqueness:

In $\tilde{k} = \left(\frac{B}{(1+\alpha)\beta(1-\beta)}\right)^{\frac{1}{\beta-2}} - K$, O admits an inflection point.

Uniqueness of the minimizer is ensured by the fact that: $\frac{\partial O}{\partial k}(\tilde{k}) < 0$.

Results discussion:

In order to explore the overinvestment decision of tenants in different contexts, we optimize the objective function and remove solutions at which the "cap" constraint is violated. We perform such a task using standard Python optimization tools (Scipy). We generate instances by varying the 3 key parameters that are the unit back-up cost (B), the scaling factor (β) and the tenants' own capacity requirement level (K). The following figures represent the results of this optimization process for a number of trials. Results interpretation give insights on the drivers of the strategic overcapacity setting.

Model output

The way we proceed to analyze the model results is based on varying one

parameter by little increments and observe the results of those series for different values for another parameter. We choose extreme values and central values to observe the impact on the series. One parameter remains fixed. By changing the value of the latter we obtain several charts representing a number of series equal to the number of values we retained for the second parameter. In the first set of outputs we will focus on the impact of unit back-up cost on the overinvestment decision and the differences observed for different values of the 2 other key parameters.

We then look at the tenants' capacity size proceeding the same way and we finish by the analysis of the scaling factor.

Figure 4.2 depicts the influence of unit back-up cost level on k^* . A general pattern regarding the behavior of this solution with respect to this parameter is a "concave shaped" response. For low values of B the overinvestment is

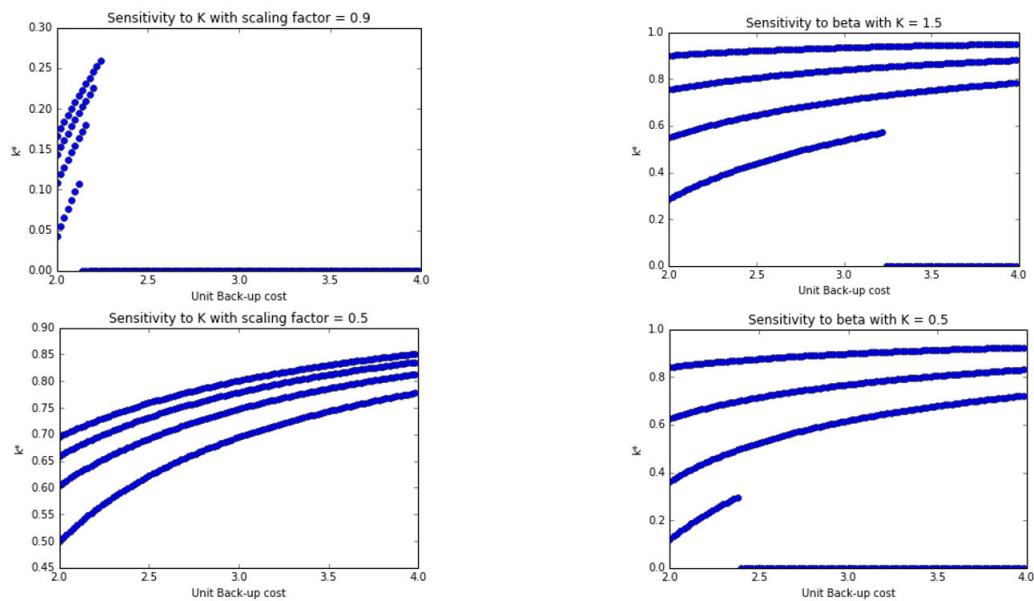


Figure 4.2: Impact of the unit back-up cost

more sensitive to changes than in the range of higher values. k^* is increasing in B but whenever reaching some threshold the optimal decision is to not overinvest at all ($k^* = 0$). This is explained by the form of the objective function and the global efficiency constraint we face in the tenant's problem. Indeed for low values of B an increase in k^* is supported by an higher opportunity cost to be avoided but if B is too high it means that the overall expected cost of sharing the infrastructure would be too high since expected back-up cost is high even in case of additional overinvestment. Regarding the influence of the two other parameters levels on the response of k^* to B , we observe that the more K is high, higher values are more frequent. Higher K supports higher levels of k^* in two ways. First it shifts response curves upwards and second it pushes forward the threshold at which overinvestment would vanish (see 4.2, left-hand side graphs).

Economically it means that bigger tenants (in terms of their capacity requirements K) tend to overinvest more. Indeed, the direct cost of overinvestment ($I(K + k^*) - I(K)$) in that case is relatively lower so that investment is more profitable (thus higher *ceteris paribus*).

Moreover, for this reason, higher values for the back-up cost is admissible regarding the choice to overinvest. The scaling factor level does have the same properties (see 4.2, right-hand side graphs).

If we now look at the response of optimal overinvestment to the level of K (Figure 4.3) we observe that everything held constant, k^* is again increasing and concave in K . Here solutions vanish for low values of K (the reverse that we observed for B). The interplay with other parameters exhibits the following properties. For lower β and higher B (left-hand side graphs) the response curves are moved upwards. A difference is that more favorable (lower) values of the scaling factor induce positive values for k^* . In fact, a better (lower)

scaling factor compensates for relatively low values of K because it moves the direct cost function downwards. To induce a given level of overinvestment, those 2 parameters are "substitutes". For B (right-hand side graphs) the effect on the curves is different. Positive overinvestment occurs whenever K is high enough to have a low enough marginal direct cost compared to the marginal back-up cost (at a given B). This is because whenever K is "too low" the direct cost function not allows to gain enough on the opportunity cost side by overinvesting in k . Given B , above this threshold, values for k^* are higher when K is higher (lower marginal direct cost). Following this, for lower values of B (*ceteris paribus*) the opportunity cost advantage derived from overinvesting being reduced, overinvestment levels are relatively lower. Figure 4.4 indicates the following for the effect of β on k^* . The response to higher scaling factor is a decrease in the overinvestment level which can vanish for some threshold values. The thresholds notably depend on K and B . The thresholds are reached for lower values of β in higher values of B (right-hand side graphs) and lower values of K (left-hand side graphs). For higher values of B the overinvestment level (response curves) is higher but vanishes earlier when increasing β . As stated above K and β are cost "efficiency" parameters so that they affect the marginal cost of achieving expected back-up costs savings. The trade-off resolution (cost minimization problem) then imply that a less efficient cost function will induce lower overinvestment and at some point (the thresholds) would vanish (due to the total cost constraint).

Thus for higher scaling factors, the overinvestment level will decrease. The impact of K is different since it also makes the response curves higher but for higher values of that parameter, the vanishing threshold is reached for higher values of the scaling factor because those 2 parameters play a similar role.

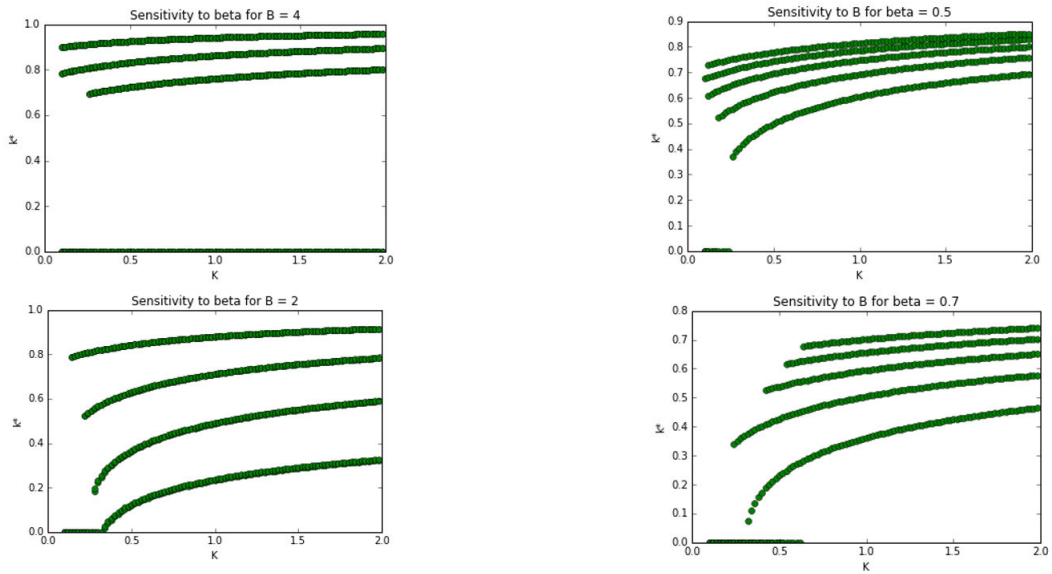


Figure 4.3: Impact of the tenant's capacity size

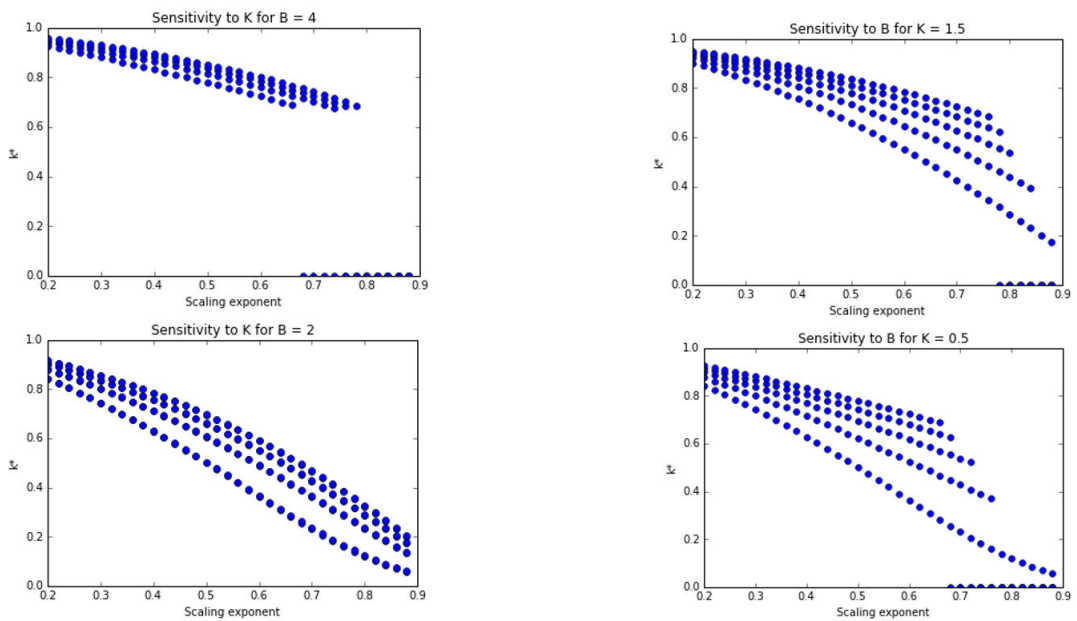


Figure 4.4: Impact of the scaling factor

Extensions

Using results obtained in the baseline model we will extend the set of parameters at stake in the model to take into account other economic aspects of such strategies. First we implicitly assumed so far that the tenants could extract all the surplus from the entrant (they do have all the bargaining power). We will show what are the consequences of different repartition of this bargaining power between tenants and entrants regarding overinvestment decision. Second we will consider time value of money in the model. Indeed the time at which entrant will be willing to access the infrastructure and pay for it can be delayed so that its payment must be discounted. We will simply add this feature assuming that achievable value for the tenants will be depreciated due to this. To finish we will analyse the impact of a use unit-cost difference between using the shared infrastructure and a standard one. Adding this we can show the impact of using substitution resources to operate the infrastructure and then integrate the 2 types of synergies in industrial ecology in a simple way. Advanced extensions will set the programmes associated with uncertainty on load profiles congruence and activity levels.

The impact of economic conditions:

We add in our baseline model the time value of money, bargaining power and substitution resource cost advantage to extend the analysis of the drivers of infrastructure sharing synergies.

Lets denote $\delta \in [0, 1]$ the depreciation factor, $\theta \in [0, 1]$ the bargaining power of the tenants, S the unit cost of the standard infrastructure use and s the unit cost of using the shared infrastructure. We notably assume that $B > S \geq s$ since we consider that s is the cost of using the common infrastructure which is using a substitution resource (input/energy/utility) to which it has exclusive access. Integrating those new parameters in our model we obtain the

following program:

$$\begin{aligned} & \min_k \{ \delta \theta \mathbb{E}(\mathbb{B}(k)) + I(K + k) \} \\ \text{s.t: } & I(K + k) + \delta \theta \mathbb{E}(\mathbb{B}(k)) \leq I(K) + \delta \theta \mathbb{E}(I(x)) + \delta \theta (S - s) \mathbb{E}(x) \end{aligned}$$

We thus can easily assess the negative impact of those new parameters on the solutions profiles as we did in the last part. Notably the impact of θ and δ is similar but their impact on the frequency of positive solutions will depend on the difference between $\mathbb{E}(\mathbb{B}(k))$ and $\mathbb{E}(I(x))$. From our assumptions and the concavity of I we know that $B\mu > I(\mathbb{E}(x)) > \mathbb{E}(I(x))$.

As a consequence (in comparative statics) the effect of θ and δ on the "frequency" of positive solutions will change at a point \hat{k} which is unique and is such that $\mathbb{E}(\mathbb{B}(\hat{k})) = \mathbb{E}(I(x))$.

For all $k > \hat{k}$ the "bad" effect overcomes the "good" one. The effect is to lower the overinvestment level since it lowers to opportunity cost not to invest. The cost advantage of using the shared infrastructure does not affect the size of positive overinvestment but allow for having positive overinvestment in situations in which it was null before. This supporting effect is dampened by the bargaining power and depreciation rate coefficients.

4.2.3 Capacity oversizing under uncertainty-MinMaxRegret criterion

Baseline model

Departing from the expected profit framework, in this section we develop a model dealing with the same overarching economic problem of overcapacity setting by tenants but in a robust optimization perspective. To do so we selected the *min-max regret approach* to adress our capacity setting problem.

The key difference with the Laplace criterion used in 4.2.2 is that the criterion we will now use does not balance the possible states of the world in a compensatory manner. The min-max regret criterion is based on the definition of a regret function. A regret function defines the distance at which a given solution is to the optimal one in terms of objective function value. This optimal reference is the optimal solution that would have been chosen if we knew the information which is actually uncertain beforehand. Facing uncertainty the attitude is thus to find a solution providing an outcome which is "not that far" from the ideal one in every state of the world. Regarding our decision problem this approach is well suited since we can easily define what is the best solution once entrant's requirement is known and that the decision in a "one shot" irreversible decision. All the model basic elements (and thus notations) remain the same as in the previous section. Nevertheless the objective function will dramatically change in line with the alternative approach we now use.

The regret function definition:

Since we know the optimal solution in the deterministic case that is setting exactly the capacity to the entrant's requirements level ($k^* = x$) we are able to determine the regret function associated to a given ex-ante incremental capacity choice k . The regret function $r_k(x)$ is derived from the difference between the best solution ex-post (given the requirement level of the entrant) and the value of the objective function given the chosen additional capacity k .

$$r_k(x) = \begin{cases} I(K+k) - I(K+x) & , k > x \\ B \cdot (x-k) - (I(K+x) - I(K+k)) & , k \leq x \end{cases}$$

As explained above the criterion we will use is the "min-max-regret" criterion. Our robust optimization problem is thus defined as:

$$\min_k \{ \max_x \{ r_k(x) \} \}$$

Results: the robust solution

The shape of $r_k(x)$ given k is described in the following:

Proposition-1:

For $k > x$, $r_k(x)$ is decreasing and convex in x .

Proof:

$$\begin{aligned} \frac{\partial r_k}{\partial x}(x) &= -(1 + \alpha)\beta(K + x)^{\beta-1} \leq 0 \\ \frac{\partial^2 r_k}{\partial x^2}(x) &= -(1 + \alpha)\beta(\beta - 1)(K + x)^{\beta-2} > 0 \end{aligned}$$

Proposition-2:

For $k \leq x$, $r_k(x)$ is increasing and convex in x .

Proof:

$$\begin{aligned} \frac{\partial r_k}{\partial x}(x) &= B - (1 + \alpha)\beta(K + x)^{\beta-1} \geq 0 \\ \frac{\partial^2 r_k}{\partial x^2}(x) &= -(1 + \alpha)\beta(\beta - 1)(K + x)^{\beta-2} > 0 \end{aligned}$$

Inner program resolution:

Regarding the inner program $(\max_x \{ r_k(x) \})$, by definition, for $k = x$, $r_k(x) = 0$.

From propositions 1 and 2 it follows that:

Proposition-3:

For $k \leq x$, $r_k(x)$ is maximized for $x = 1$.

Proposition-4:

For $k > x$, $r_k(x)$ is maximized for $x = 0$.

Global program resolution:

Regarding the global program $\min_k \{ \max \{ r_{k \leq x}(1), r_{k > x}(0) \} \}$ the solution k^{**} is the solution equalizing $r_{k \leq x}(1)$ and $r_{k > x}(0)$.

$$k^{**} = 1 - \frac{I(K+1) - I(K)}{B}$$

Figure 4.5 depicts an illustration of the solution for $K = 1$, $\beta = 0.7$ and $B = 5$, resulting in $k^{**} \approx 0.75$.

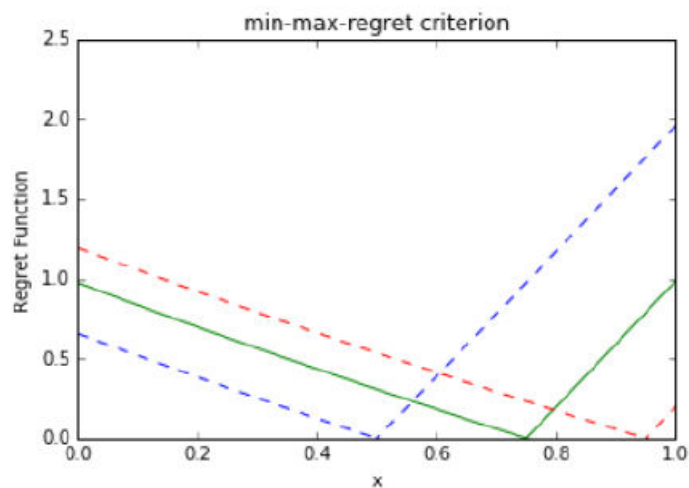
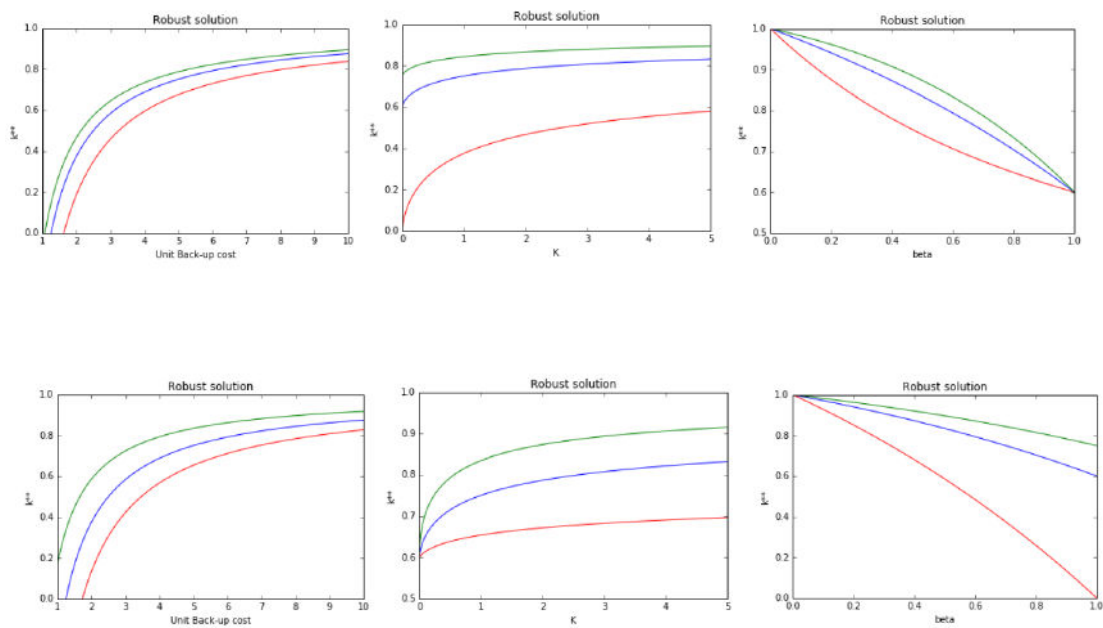


Figure 4.5: Program solution illustration

Results: model output



In order to investigate the decision outcomes in this new framework, we simulated the optimal solution response varying each of the 3 parameters. Having derived the analytic solution of our robust optimization problem we will investigate how does the solution (k^{**}) behaves with the main techno-economic parameters. In each case we set 3 different values for a second parameter to observe the differences generated. This cross analysis is performed using a set of values to parametrize the solution curves. Colors encode the less favorable case in terms of overcapacity setting (red curves) and the most favorable case (green curves) as well as intermediate cases (blue curves).

Case 1: The influence of K on the capacity choice (first line and second column graph)

The optimal solution is increasing and concave in K and ranges in higher values when B is higher given a particular scaling factor (here 0.7). Moreover for higher values of B the optimal additional investment in capacities is less sensitive to variations of K . Results depicted in the graph below (second line and second column, with $B = 5$) show that the solution ranges in higher values for lower scaling factors and that it is more sensitive to variations in K for lower values of β especially in the range of low values of K .

Case 2: The influence of β on capacity choice (third column graphs).

The solution is decreasing and concave in β and ranges in higher values for higher back-up unit cost (B) for a given K (here $K = 1$). It is also more sensitive to β for low values of B (bottom graph). Solutions are far from each other when varying B for high values of the scaling factor. Optimal overcapacity is also decreasing in β for different values of K . However its second order properties varies from one level to another being convex for low values of K ($K < 1$) and concave for high ones after having switched for intermediate values (around 1). The more K is high, the more the solutions

ranges in higher values (top graph). Solutions differ more for intermediate values of β when varying K .

Case 3: The influence of B on capacity choice (see first column graphs).

Optimal solution is increasing and concave in B (less sensitive to variations in B when B ranges in higher values). It is also highly sensitive to changes in K in the range of low values of B and less sensitive the more we range in higher values of B . The higher is K the higher is the solution level range (top graph). The solution behaves the same way according to the level of β for a fixed K (bottom graph). Extensive simulations trials confirmed that the observed patterns are robust to all admitted changes in the value of the parameter that remains fixed in the illustrative examples provided hereabove.

Extensions

Following the same logic than in the Laplace criterion based model, we investigate the effects of bargaining power, value depreciation rate and infrastructure use cost advantage on the solutions. To do so we keep the same notations.

Regret function modification:

The introduction of those parameters will affect the form of the regret function. Considering those additional parameters the regret function becomes:

$$r_k(x) = \begin{cases} I(K+k) - I(K+x) & , k > x \\ \delta\theta(S-s) \cdot (x-k) + \delta\theta B \cdot (x-k) - (I(K+x) - I(K+k)) & , k \leq x \end{cases}$$

The influence of the new parameters in fact only changed the right-hand side part of the regret function. Following this, the resolution of the outer program requires (ceteris paribus) to increase (or decrease) k^{**} so as to reduce (to increase) the level of the right-hand side regret while increasing (decrease)

the left hand side one. Analytically this is encompassed in the new solution definition that we derived the same way as in the first formulation, that is:

$$k^{**} = 1 - \frac{I(K+1)-I(K)}{\delta\theta(S+B-s)}$$

As a consequence we have that higher (that is more favorable) values of δ and θ increase the overcapacity which is optimally set. Regarding the cost advantage derived from using a substitution resource ($S - s$) the effect is the same. The decision is notably dependent on the product of those additional parameters. Indeed, higher appropriability of higher cost advantages induces higher overinvestment by the tenants.

4.2.4 Capacity oversizing under uncertainty: non-cooperative formulation

The problem formulations developed so far were built considering that the overinvestment decision and the subsequent pricing of this additional capacity for entrants were determined cooperatively by the tenants. In this section we will depart from this assumption by addressing the situation in which (two) tenants would rather choose to set their own capacity level and access prices non-cooperatively. The interest of such an additional formulation is twofold: First it can give bounds for cost and benefits repartition in the cooperative case among tenants and second it can address cases in which tenants can not pool their capacity needs and share a common infrastructure for strategic or geographical/physical reasons. To investigate the non-cooperative case we will use the first formulation analyzed in this work that is the Laplace criterion. The other formulation indeed is less straightforward to investigate and use since it requires an unambiguous best-decision to be used in the regret function building. This extension could be considered for further work.

Model:

In addition to the standard notations and model elements used and explained in the cooperative cases, we introduce variations in the model structure to represent the new business context. For simplicity we will assume that only 2 tenants (a and b) invest and compete in the model. We will use the same cost structures and thus parameters than in the cooperative models (4.2.1, 4.2.2). We assume that the two tenants have access to the same technology for the infrastructure so that the investment cost function is symmetric (α and β are similar among tenants). The only factor differing from one tenant to the other is the capacity requirement level K_i and we assume that "a" is bigger than "b" that is $K_a > K_b$. More importantly, since we now assume that the two tenants behave non-cooperatively they do master their own strategic variables. The game is structured according the following timing. Tenants do have different nominal capacity needs $K_a > K_b$. After having set simultaneously their overcapacities in a first period (k_a, k_b) they compete to attract new users in a second period after uncertainty about the entrant's capacity need x has been resolved. To do so each tenant sets an offer to the entrant composed of an amount of available capacity k_i and an access price to have the right to use this capacity (P_i). Assuming that the entrant cannot access both infrastructures since we argued it was initially not possible to pool the capacities of the two tenants for exogenous reasons, facing the 2 offers, the entrant choose to access either infrastructure "a" or "b" (or none and then builds its own). Having stated the game structure we now explain what are the non-cooperative equilibria that can occur integrating the two key strategic decisions (overcapacity investment and subsequent access pricing).

Equilibria:

If $k_a = k_b$, then due to Bertrand competition, ex-post access prices will be set

at 0. This strategy is not stable for any player since it provides in expectation a null gross payoff ex-post whatever the realization of x that is a negative expected profit (due to overinvestment incremental cost which is sunk).

Moreover, at this point, no tenant i has interest to lower its overcapacity choice by setting $k_i - \epsilon$ (with $\epsilon > 0$) since he will in consequence never be able to compete ex-post against j 's offer (notably in cases where $x \geq k_i - \epsilon$). Thus the only strategy is to set $k_i > k_j$ in order to win the price game in period 2 (notably when $x \geq k_i$). Following this, tenant's mutual best responses thus induce increasing overcapacity setting in period 1 until their respective expected profit vanishes that is until their objective function is lower than their respective constraint. The value achievable by the tenant who invests more than the other is dependant on the expected profit conditioned by the lowest investment level (the value difference for a part of entrants, the ones who have a requirement above this lowest level). The constraint we faced in the cooperative program changes in this setting. Tenants must derive a positive expected profit (π_i being the profit of actor i) by overinvesting in k_i anticipating competition in period 2. Thus the profitability constraint being stated as:

$$\mathbb{E}(P_i(k_i, k_j)) \geq I(K_i + k_i)$$

$$\text{where: } \mathbb{E}(P_i(k_i, k_j)) = 0 + \max(\mathbb{E}\mathbb{B}(k_j, x) - \mathbb{E}\mathbb{B}(k_i, x), 0)$$

$$\text{Thus, } \mathbb{E}(\pi_i(k_i, k_j)) \geq 0 \iff \max(\mathbb{E}\mathbb{B}(k_j, x) - \mathbb{E}\mathbb{B}(k_i, x), 0) \geq I(K_i + k_i)$$

As a consequence, 3 equilibria can occur:

1) "Natural Monopoly equilibrium":

From the reasoning developed hereabove, a first equilibrium is characterized by the following outcomes for players a and b: $k_a^e = k_a^*$ and $k_b^e = 0$. This is the case in instances where : $\mathbb{E}(\pi_b(k_b^*(k_a^*))) \leq 0$ and $\mathbb{E}(\pi_a(k_a^*, k_b^*(k_a^*))) \geq 0$. with k_a^* the optimal monopoly overinvestment (the same as in the cooperative

case).

Proof: If "a" can deter b's competition by investing in $k \leq k^*$ then a can simply optimize its capacity choice as if it would have been alone. "a" is thus a natural monopoly due to its relative size $K_a > K_b$.

2) "Standalone equilibrium":

In cases in which "a" would optimally set a null overcapacity in the monopoly setting then "b" would do also and no capacity increment is invested in $k_a^e = k_a^* = 0$ and $k_b^e = 0$.

Proof: since $K_a > K_b$, "a" does have more favorable conditions to overinvest (see-cooperative case results). In consequence if it is optimal for "a" to not overinvest it will be also the case for "b".

3) "Strategic deterrence equilibrium":

A third set of equilibria consists in the following:

$k_a^e = k_a^* + k'_a$ and $k_b^e = 0$. This outcome is generated in the cases where: $\mathbb{E}(\pi_b(k_b^*(k_a^*))) \geq 0$ and $\mathbb{E}(\pi_a(k_a^*, k_b^*(k_a^*))) \leq 0$ with k_a^* the optimal monopoly overinvestment (cooperative case) and k'_a is the (minimal) capacity increment such that $\mathbb{E}(\pi_b(k_b^*(k_a^* + k'_a))) \leq 0$ and $\mathbb{E}(\pi_a(k_a^* + k'_a, k_b^*(k_a^* + k'_a))) > 0$.

Analysis:

All those equilibria are driven by the size differences between the competing tenants and their "absolute" size. If tenants are both "small", "Standalone equilibrium" will be more likely to emerge. For "big" tenants equilibria will depend on their relative size. Close tenants would generate equilibrium 2 or 3. Whenever "a" is far from "b" and the two do not belong to the same range of sizes, "a" will be likely in a natural monopoly status.

4.3 Synthesis and recommendations

In this chapter we proposed models dealing with infrastructure/service sharing synergies. In a first part we insisted on the nature of such synergies by formulating it as an integrated capacity choice and capacity use problem. More precisely we show that this type of synergies is induced by 2 associated mechanisms one pertaining to the choice of a (minimal) capacity level to satisfy capacity requirements of the users and another one related to the degree of economies of scale exhibited by the capacity cost function. After having set the basics of infrastructure sharing synergies, we proposed an economic model dealing with the integration of capacity choices and capacity use. The economic model we proposed is generic enough to be adapted to different cases and its key characteristics are the following. We split the set of individual actors in 2 categories, the "tenants" and the "entrants". The tenants are actors deciding what capacity level must be set. Tenants thus incur an investment cost. The entrants do not have the power to decide what is the capacity level to be installed but they can access the infrastructure to use it and thus incur an access cost. The access price is determined by private negotiations between tenants and entrants after the capacity has been set so that this choice is made under uncertainty by the tenants.

We show that tenants' decision about capacity is made on the basis of a cost minimization problem under uncertainty. Our economic model 3 key parameters drives this choice that is the tenants' capacity requirement level (denoted as "K"), the degree of economies of scale exhibited by the infrastructure at stake (" β ") and the unit back-up cost that infrastructure users might incur in case of capacity congestion (B). In practice we then advocate to identify those 3 parameters carefully for the tenants' in an eco-industrial park. Capacity requirements of the tenants must be well established before-

hand so as to know what is the relevant part of the capacity cost function to be considered to value overinvestment. Then the capacity cost function should be established on the basis of actors own experience on the building of such infrastructures. We argue that an internal process could be worthwhile to better anticipate the capacity cost function. Engineering economics literature frameworks can help practitioners to structure such a process. Lastly, back-up costs data should be available so as to account for the "opportunity cost" part of the objective function.

Regarding our model results, K and β are substitutes because they act on the capacity cost function shape. The impact of B on capacity choices is to provide an incentive to overinvest since it is an opportunity cost to not overinvest. Nevertheless when the capacity cost function is not very efficient (low degree of economies of scale and/or little tenants') a high value of B can hinder sharing practices since the total cost of the shared infrastructure would be very high compared to a the alternative solution consisting in infrastructure duplication. Investigations towards additional economic considerations led us to conclude that higher time value of money and lower bargaining power of the tenants tend to limit the likelihood of sharing. On the contrary we showed that if the shared infrastructure proposes unit-use costs advantages (because it allows to use substitution resources like in IE) then the willing to overinvest (and then to share the infrastructure) is increased thus demonstrating a positive link between the 2 synergies archetypes.

In a last contribution we showed that whenever several groups of tenants (for example 2 EIP) compete to attract future entrants, 3 equilibria can occur depending on the relative sizes of the parks.

Our results notably show that "big" enough parks tend to overinvest more and attract more easily entrants thus generating an anchoring effect.

Chapter 5

Conclusion: results and perspectives for eco-industrial parks development

Progress and continuous development of human society faces nowadays environmental challenges leading us to rethink the underpinnings of economic system functioning. The circular economy paradigm proposes a shift of a linear unidirectional model of production-consumption to new modes of organisations in favour of resources conservation. Industrial Ecology proposes frameworks, concepts and tools suited to cross-over organizations towards sustainability of production systems and this is an appealing approach to make the circular economy principles working out.

Departing from a clarification of the concepts and units of analysis required to analyze its implementation in real systems in function, our work thus investigated the key challenges and dimensions at stake when dealing with the application of I.E principles towards the realization of industrial symbioses. To do so we recalled the importance of the human and cross organizational

nature of the solutions proposed in this approach so as to consider its implementation as a process involving many actors along different steps whose effectiveness is conditional upon mutual multilateral commitment to a (set of) transaction(s) that we study using economic modelling in this thesis report.

Investigations and results summary

What is industrial ecology in practice ?

As a starting point we described in detail the value creation schemes behind the two archetypal synergistic practices inspired from industrial ecology perspective: "resource substitution" and "infrastructure / service sharing".

We demonstrated that while the former is based on "vertical" relationships targeting operational cost savings through input mix switches, the latter consists in investment cost savings stemming from the "horizontal" use of a capacity level by several actors. Resource substitution value is dependent on the difference between the savings achieved from reduced standard resource use and/or avoided disposal costs and the total cost required to give the client access to the substitution resource. Transaction is thus mutually worthwhile if the traded volume and its unit value allow to recover investments in equipments (for collection, pre-treatment, transfer and use at the client's site). In the case of grassroot investment, infrastructure sharing value comes from the degree of economies of scale exhibited by the shared equipments and for a given capacity value depends on the degree of complementarity between each actors load profiles (that is the total capacity needs) in order to avoid back-up expenses (congestion costs).

After having clearly set the economic characteristics of those 2 archetypal synergies we built (for each) a taxonomy of real world synergies practices.

We constructed this taxonomy by analysing the nature of flows and shared infrastructures within a set of 24 eco-industrial parks in the world. At this point we were surprised by the scarcity of detailed studies on such initiatives so that it motivated the undertaking of a case study in the thesis, the Green Valley EIP in France to offer one more in-depth case to researchers and practitioners in the field. From the study of those 25 EIPs, we identified the following forms of resource substitution synergies classified along their physical nature and the use patterns observed.

The "material to material" type where the resource is either used directly, as a complement in a mix of inputs or purified to be recycled. Then the "material to energy" type with 2 modalities that are direct conversion (combustion) or conversion to a fuel (to be used after). The last category is the "energy to energy" type in which vector is converted (cogeneration) or used directly (heat transfers and cooling).

Regarding the taxonomy of infrastructure / service sharing we classified the practices by functionality and further in the nature of the equipments involved. As a result we identified sharing targeting "self-production" of resources along 3 modalities (CHP plants, waste water exchange networks and miscellaneous conversion platforms) and sharing of "treatment" equipments. The latter comprising the common use of waste water treatment plants and boilers (incinerators and CHP plants boilers). We added to this taxonomy 2 categories not specifically inspired from industrial ecology principles : Purchasing (order pooling) and Logistics (inventory pooling and freight consolidation).

This taxonomy is helpful to target and prioritize the good practices prone to be launched. It can be used in territorial diagnosis to identify and classify potential synergies. This taxonomy can (and might) be notably completed

dynamically by future researches on industrial symbiosis since it depends on the set of available information on successful initiatives all around the world.

Towards EIP development, literature contributions

In terms of analytic methodologies, the state of the art conducted exhibits 3 type of contributions. A first is the "diagnosis" tools aiming at identifying the available substitution resources and potential users in a given territorial area. The goal is to give information to actors so that they can begin to study and design in more details the exchange opportunity raised by the user of such diagnosis tool. In France we can notably signal the existence of 4 dedicated softwares (Presteo, Comethe, PS2E-SymSim¹, ActIf²).

In addition to empirical tools, a stream of research investigated the definition of tailored "performance indexes" for EIPs. Economic assessments are still conducted with standard tools (annualized costs or Net Present Value-NPV) adapted to the accounting of savings induced by resource substitution at a flow level. At the EIP level some indexes have been proposed to guide the recruitment process of tenants accounting for the impact on global measures after reconfiguration. Environmental criteria are a last subset of indexes proposed in the literature on EIPs and they propose the assesment of saved resources, circularity degree or avoided emissions or pollutants.

The third set of contributions on modelling techniques tailored to IS and EIP is the set of "design and optimisation" tools. Most models performs the network design of flows within EIPs. Such models are formulated as mixed interger programmes (MIP) and matches resources with sinks designing a network of piping systems. Most of applications target utilities as waste water, heat and steam. Models taking into account conversion steps might offer

¹<http://institut-ps2e.com/recherche/ecoparc/>

²website: <http://www.cci.fr/web/developpement-durable/actif>

additional insights for the analysis of "material to material" and "material to energy" types of synergies.

Moreover, by design, those models suffer from the lack of consideration of individual actors preferences over the available transactions and information problems. Recent contributions made an attempt to introduce such considerations in optimisation models using solution concepts imported from cooperative game theory and using fuzzy programming in a satisficing perspective (Tan et al., 2016; Ubando et al., 2016; Andiappan et al., 2016). Such approaches are of first interest and we call for a research effort towards such methods in order to address the key issue of individual actors (local) preferences over possible opportunities in EIPs (Leong et al., 2017). Such formulations might integrate constructs representing information on load profiles adequation to model preferences more accurately.

In line with the former remarks we investigated the socio-economic dimension of EIPs and IS in the second section of chapter 1. We began by stating a new definition of EIPs by contrasting them with other forms of clustered businesses following arguments from different streams of the literature. We thus defined EIP as " [...] an open community of actors striving for economic and environmental efficiency of their production and use processes leveraging shared assets and/or using waste and by-products as substitution resources ". After what we recalled results from the literature and proposed a characterization of economic roles of actors in an EIP (resource sources, sinks, processors, conveyers) insisting on a set of strategies affecting the generated value (massification, diversification, consolidation).

Taking into account actors' roles we proposed a structuration of the complex process turning (or not) an I.E inspired initiative into the effective realisation of synergies through the mutual commitment to a transaction. The upstream

is composed of information acquisition (and concept recognition) and is followed by adhesion of actors (or not) then detailed study/evaluation phases involve design sub-process feed by upstream information and new information disclosure (process, quality requirements, load profiles ...). Negotiation follows up the design phase and cycles with it until an agreement is reached (or proven impossible) and the actors commit to the contract. In last "downstream phase" are the launching and exploitation of the synergies. Regarding contributions in the literature about social aspects in EIPs, we found contributions in sociology and complex systems modelling. The former set of articles proposes to investigate the influence of key sociological aspects explaining the success and form of industrial symbiosis. The key concept having received attention is "short mental distance" induced by "social embeddedness". Despite theoretical arguments that predict a strong influence on the realization of synergies, empirical studies using social network analysis did not demonstrate correlations between the quality of inter-personal relationships and the outcomes in terms of exchanges in EIPs. Nevertheless few studies have been undertaken so that more research is needed to address the robustness of this conclusion (Ashton, 2008). Other complex systems approaches have been used notably Agent-Based Models (ABM) with several contributions. In ABM the rules of interactions between the individual actors are fixed (exogenous) and the simulations only give insights on population-level patterns which makes it a suitable approach to study aggregated behavior in large scale populations which is not the case in EIPs. We argued that game theoretical models are more suited to study the commitment in transactions towards IS since interaction mode is rather co-designed (negotiated) between actors so that the modelling technique should endogenize the interactions rules to understand and address the commitment issue.

Departing from theoretical approaches of actors relationships and the process of EIP and IS development, we investigated the literature on real I.E initiatives and the challenges raised and the factors driving the realization of exchanges and transactions.

As a lesson, we can state that there is a side effect of the involvement of the public actors in the planning of synergies in EIPs.

Several studies from real world initiatives indeed revealed that a too strong intrusive intervention of public actors is detrimental to the success of symbioses (Heeres et al., 2004; Gibbs and Deutz, 2005). In fact the State or local authorities can have an influence but it could be negative since it comes with information disclosure from industrial private actors and objectives misalignments. Quite often, the State proposes solutions or practices with more environmental content or stringent requirements that hinders the willingness to participate.

We rather propose that the governmental bodies interested in the development of I.E inspired synergies must set-up a "system of measures" rather than to target specific projects and being "too much" involved. We propose 3 types of interventions that must be done simultaneously to motivate IS. First incentives should be created either on the form of "resource use restrictions", "waste disposal cost" and the financing of "IS compatible" equipments drawn from our taxonomy (CHP plants, methanation, WWTP).

In addition to those 3 types of incentives, governments should consider resource substitution as an alternative authorized treatment path. Indeed due to regulations associated with the legal qualification of wastes (Waste Status) treatment paths are fixed by the law which totally prevents or restricts the use of many wastes as a substitution resource. Specific authorizations should then be made possible under some constraints on potential hazards.

The last block of policy to be leveraged to foster IS is the training and financing of EIP managers-advisors to stimulate the adhesion of private actors in the IS implementation process. Following the Korean type of EIP management (Behera et al., 2012) the EIP manager can be in charge of project management and compliance analysis for regulatory aspects quoted hereabove whenever actors would enter the design phase. At this point the financing would be partly assumed by the private actors. By this way the financial charge of EIP organization is shared between public and private actors and the manager can enter into a positive learning process about IS specificities during his missions on the design phase.

Generally speaking IS are more implemented under economic stress. IS projects even if economically sound must be financed by resources issued at a higher level in the firm organization so that internal arbitrations are not always favourable to site specific, locally oriented expenses.

Another regular pattern is that the technical complexity of products exchanged is quite low. Most exchanges concern utilities (heat, steam and water) and less complex materials (wood, plastics, ashes...). Even if the networks of exchanges seem to be quite interrelated and complex, in depth study of their deployment reveals that it has come up incrementally adding up dyadic (bilateral) arrangements. Therefore, most synergies are still very simple and issued by private actors on the basis of bilateral negotiations rather than collective farsighted planning.

Industrial symbiosis in practice, the case of Green Valley

In order to test those predictions and patterns and to provide a new detailed case study about EIPs we investigated the Green Valley EIP. This EIP is located in France in the Lorraine region and organized around the activities

of a central actor, the Norske Skog Golbey pulp and paper mill³.

This case has revealed emblematic of some patterns presented in the literature on EIPs. In fact the various synergies developed in that EIP have been incrementally set-up around the strategic shift of the Anchor Tenant (the pulp and paper mill) operated to cope with sectoral decline thus following an "anchoring process" (Sun et al., 2017).

As in many other cases, first synergies were of little technical complexity (co-location, shared WWTP use, steam exchange synergy) while later synergies involve higher degree of technicity and organisational complexity (biogas production, shared boiler and biorefinery demonstrator). Moreover the large amount of investments in local synergies have been made possible (or eased) by the "Business Unit" status of the plant which gives higher degree of financial freedom.

The interesting patterns revealed in this case study are the way regulations intricates and thus creates incentives or disincentives for resource substitution and investments in sharable assets (CHP plant). Regulation appears to be an instrument able to stimulate the installation of equipments that can be further used for IS purposes independently of the intrinsic goal of the regulation whose target was a balanced national-level energy planning. Moreover the permanent reflection of the actors towards the use of residual (unused) capacities was salient in the case study and demonstrated the interest and the way by which infrastructure sharing decisions are path dependent.

Regarding the transactional aspects long term contracts are used to manage the synergies between actors. Regulations as well as equipment manufacturers do have influence on the way contracts are constructed incrementally between transactors validating the downstream phase we introduced in our

³website: <http://norskeskog-golbey.com/>

process representation of IS implementation in which technical design and negotiation interact.

Economic modelling of eco-industrial synergies

After having investigated the literature on EIPs and IS, precised the objects of study, set-up many propositions and performed a real world case study, we focused on the development of economic modelling of the resource substitution and infrastructure/service sharing synergies, to gain insights and formulate propositions on the transactional aspects of such practices.

Transactions being our unit of analysis, we reviewed literature from economics and management dealing with the forms of economic governance of transactions.

Contracts is an intermediate form of governance in between market transactions summarized by price signals and hierarchical control. The use of contracts is dependent on conditions and costs associated to its construction, those costs being characterized by properties pertaining to the nature of transaction it materializes. Contracts are co-constructed and thus are resulting from a process in which actors establish the contract following their strategies and objectives so that cooperative game theory is the best framework to analyse how does this process is conducted and what are its outcomes. Literature offers modelling techniques to analyse economic outcomes of cooperation and the contract negotiation, both in bilateral and multilateral settings. Economics approaches were choosed as suited tools. After having choosed to analyze the commitment issue to a contract using economic tools, we showed that the business specificities characterising exchanges of substitution resources in IS are: quality concerns and customization, load profiles adequation information, need for investments in equipments and little num-

ber of potential partners induce a high degree of asset specificity. Costly fine grained information acquisition and uncertainties towards value (importantly not transaction object specification) lead to the use of complex contracts to govern the transactions over IS, in line with findings about IS development patterns.

From this basis we reviewed literature on management research and supply chain management to qualify the various forms of contracts and type of provisions that can be used in several contexts and we proposed a generic (economic) contractual architecture suited to handle specificities of IS. This architecture is composed by several fundamental building blocks in which contractors should specify: the parties to the contract, the contract object (the focal performance), the contract duration, the bill-of-specifications, the performance pricing scheme and a set of warranties and associated penalties, themselves composed of failure mode specification and corresponding penalty pricing schemes.

We then propose contractual design guidelines to precise the content of the generic contract architecture in line with resource substitution synergies and the issue of commitment. We thus framed the resource substitution contracting problem as a multi-period buyer-seller model in which 2 class of decisions pertain to the 2 contractors (the buyer and the seller) that are the "local" (at every period of the operations horizon) supply and demand order decisions and the "global" commitment to the contract decision.

Commitment is a "global" decision (made under uncertainty) since it is a one shot decision and triggers the operational phase of the synergy in which "local" decisions are made in each period on the basis of profit maximisation. By doing so we explicitly introduced the commitment decision in the contracting framework and we proposed alternative formulations of the deci-

sion problem. We then introduced operational risks characterizing resource substitution synergies: exogenous mismatch between resource (potential supply) and needs (potential demand); variability of unit cost of supplying the substitution resource and the unit value saving of using the substitution resource in place of a standard one. Having set-up the economic framework, we described the key transaction patterns to be analysed by contractors when engaging in resource substitution.

We argued that load profiles congruence, demand (and supply) flexibility degree and statistical information on unit costs and standard input prices are the key dimensions driving contractual design. Indeed, taken altogether they represent the specific risk profile of resource substitution that must be handled in a well designed contract. Using our contract architecture and the buyer-seller interaction framework with the relevant elements, we proposed a formalized contract design tailored to handle the specific risks of resource substitution. More precisely we introduced a two sided indexation scheme to price the substitution resource supply performance and we described analytically the shape of appropriate minimum-bill provisions and supply warranties. In each case, a scheme describing the penalties to be incurred in case of infringement was proposed. In the formulation of those schemes we introduced explicitly a risk sharing parameter on each penalty amount so as to explicitly state the repartition of potential damages between actors. Our guidelines indicated that exogenous and objective measures of value (costs and standard input price) must be treated with indexation while relationship specific elements related to the quantity of traded resource must be addressed using the warranty/penalty packages for which structuration might involve a variable degree of flexibility to represent a time sub-horizon over which the warranty is defined.

To summarize our contribution, we thus developed a consistent contract design framework with guidelines explaining how to establish relevant information about the required issues and how to integrate such key elements in contractual provisions. From this, we derived an appropriate structure based on formalized schemes. We also formulated proposition for further research towards the definition of alternative warranties, penalties or pricing schemes that could also be relevant in the context of resource substitution synergies. In the last chapter (4), we departed from resource substitution synergies and investigate the economics of infrastructure/service sharing synergies.

As we have shown in the first chapter infrastructure /service sharing synergies are intimately related to the concept of capacity. As a starting point we derived, using elements from the literature on engineering economics, an economic formulation of capacity costs function that is further used in our economic models formulations and show how to model the degree of economies of scale and the cost sharing problem induced by the use of a given capacity by multiple actors with different capacity requirements. Using this generic formulations of a capacity cost function and capacity use patterns, we undertook the integrated modelling of capacity choices and subsequent capacity use in order to gain in depth insights on the economic drivers and behavioral considerations influencing infrastructure sharing practices.

We developed a generic 2 period economic model where capacity users are split in 2 categories, the tenants who choose (irreversibly) the capacity level to set and the entrants who seek access to the capacity after it has been chosen by the tenants. The capacity choice is assumed to be done under uncertainty since the tenants do not know precisely which entrants will seek for capacity access that is what will be the additional requirement to fulfill in period 2. Entrants should pay a fee to access the capacity and this fee is

bounded by their willingness-to-pay (WTP). This WTP is their standalone cost net from back-up expenses in case the capacity set by the tenants is not sufficient. We showed that the problem faced by the tenants is a cost minimization problem under uncertainty where the cost function is composed of a direct cost (the cost to over invest) and an opportunity cost (the cost of assuming back-up expenses). We proposed 2 different formulations of this decision problem: one based on the expectation operator (Laplace criterion) and the other on the robust minmaxregret criterion.

Following those formulations, we showed that the key parameters driving the initial capacity choice are the degree of economies of scale, the total capacity requirement of the tenants and the unit back-up cost to be incurred in case there exists a capacity shortage (a congestion) whenever entrants are allowed to access the infrastructure capacity. Intuitively (and as demonstrated) the two first parameters foster higher capacity setting but with different sensitivities. Back-up cost has also a positive influence on the capacity which is set but, surprisingly, in the Laplace formulation we showed that, for particular ranges of values, no (over) investment occurs. This result indicates that for too high values of congestion costs the total expected cost would be too high compared to a simple infrastructure duplication to justify overinvestment so that no further synergies will be realized. We completed the former models formulation by introducing additional economic parameters to investigate their effects on the investment in capacities and the relevance of infrastructure sharing. Bargaining power imbalances and high time value of money hinder the investment levels by tenants while the existence of a unit cost advantage of using the shared infrastructure (typically to benefit from a resource substitution synergy) does favour overinvestment and thus sharing opportunities demonstrating a clear link between the two archetypes of eco

industrial synergies. In a last contribution, we extended the former economic model by introducing competition between 2 groups of tenants to attract potential entrants. This non-cooperative formulation allows us to conclude that depending on the relative difference of the tenants "sizes", 3 equilibria can occur that is one in which no synergies are generated (duplication) and 2 in which the "bigger" tenant overinvest while the "smaller" does not. If the competing tenants are closed enough in terms of size the bigger overinvest sub-optimally. This model could be further extended to take into account more complex strategic contexts in which coalitions can be formed.

Research perspectives and further issues

The realization of industrial ecology through the development of eco-industrial parks is an appealing way to put the circular economy principles into practice. EIP can improve the sustainability of local, regional and thus in an aggregated way, global industrial activities facing concerns of resource scarcity, pollution and energy losses. Further implementation of EIPs in the world could contribute for 11 to 16 % of industry sector abatements towards economy decarbonation for a 2 degrees global warming objective in 2050 (that is around 3% of global abatements) as stated in Alazard-Toux et al. (2015). Despite its interest for practitioners and scholars many challenges still remain to its wider implementation.

Actually few eco-industrial initiatives gave birth to effective industrial symbioses across the world. Industrial ecology related concepts are still quite confidential and would deserve more public awareness in order to stimulate the undertaking of more initiatives globally. Moreover, once initiated, synergies projects should reach an higher rate of completion to put the ideas at work in systems in function. This evolution of industrial practices needs

more than a wishful thinking to play a key role in environmental and energetic transition which is required by human development. In this work, we thus reviewed the contributions trying to understand, assess and create eco-industrial parks and we pointed out the need for consideration of fine-grained processes involving individual decision makers in the analysis of industrial symbioses implementation. Thereby, we complemented the contributions on eco-industrial parks and industrial symbioses following the latter line of inquiry. The importance of the topic and the number of remaining challenges urge further research.

First, more work is needed on the identification and in-depth study of additional (potentially) existing eco-industrial parks in the world.

Such a contribution is decisive to gain understanding of the drivers of symbioses implementation. We propose to frame such investigations with the process representation we developed. Following this, future researches must carefully analyze both favorable and unfavorable factors in a wider set of initiatives so as to look at both type of influences. Those analyses can allow other authors to complement or precise the taxonomy we built in our contribution.

Second, the analysis of public interventions schemes through regulations, policies and direct participation to synergies should be undertaken. Economic modelling can be used to fulfil this objective notably regarding the latter. This work must be conducted in line with an additional reflection on the objectives public actors might be committed to. To do so we advocate an in-depth study of "rebound effects" and "lock-ins" associated with IS. Regarding sustainability, the last phenomena must be understood to take into account the short term, medium term and long term effects of IS implementation in industrial ecosystems.

Accordingly, the state (or public actor) interventions can be modelled in the Principal-Agent framework (with EIP as the Agent) so as to understand the impact of applicable interventions schemes (landfill taxes, CO₂, water withdrawal constraints, infrastructure funding, waste use authorization ...).

A third research direction we propose is to extend our economic models so as to go further in the understanding of specific IS related issues notably load profiles mismatches. Regarding contracts architecture in the context of resource substitution synergies, the basic structure and provisions we proposed can be used to simulate many resource exchanges and investigate the influence of different decision criteria under uncertainty (notably the chance constraint formulation) on the applicable contracts. Moreover this contractual framework may be enhanced investigating problems with several suppliers and/or several buyers using a portfolio of such contracts to manage the IS specific risks. To go further, option contracts (whose value might change depending on the degree of demand flexibility) could also be studied as an alternative solution to our proposed supply contracts forms.

Infrastructure/ service sharing economic models we proposed can also be used as a basis to analyze additional dimensions of such type of synergies.

A first extension we propose is to introduce an additional uncertainty on the load profiles adequation between tenants and entrants. Such an uncertainty would interact with the requirement level uncertainty so that the final net requirement would be dependent upon the load profile adequation degree. Models should be adapted to take into account this parameter and we guess that the tenants' own peak requirement level can drive a lot the problem solution since it will interact with load profiles adequation degree (for which an appropriate construct might be built). An additional extension we recommend could be to use coalitional games representations (and concepts from

cooperative game theory) to determine the actual tenants' peak requirement level. Indeed, introducing the load profiles information into the problem, a set of EIPs' tenants would play a cooperative game to set infrastructure sharing partnerships. Results on the (potential) stability of the grand coalition (the EIP) might be informative on the way such arrangements occur and what are the equilibrium matches within an EIP.

From those results, one can further integrate the problem with the former (overinvestment under uncertainty) so as to obtain a detailed and complete model of the infrastructure sharing synergies implementation.

Findings on those research questions will close the loop.

Bibliography

Hamid Afshari, Romain Farel, and Qingjin Peng. Improving the resilience of energy flow exchanges in eco-industrial parks: Optimization under uncertainty. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 3(2):021002, 2017.

A Agarwal and Peter Strachan. Literature review on eco-industrial development initiatives around the world and the methods employed to evaluate their performance/effectiveness. *A report prepared for Databuild, UK, The Robert Gordon University*, 2006.

Nathalie Alazard-Toux, Patrick Criqui, Jean-Guy Devezeaux de Lavergne, Laetitia Chevallet, Sylvie Gentier, Emmanuel Hache, Elisabeth Le Net, Philippe Menanteau, Frederic Thais, et al. Decarbonization wedges report. Technical report, 2015.

Vito Albino, Luca Fraccascia, and Ilaria Giannoccaro. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. *Journal of cleaner production*, 112:4353–4366, 2016.

M Josune Albizuri. The α -serial cost-sharing rule. *Mathematical Social Sciences*, 60(1):24–29, 2010.

- M Josune Albizuri and José M Zarzuelo. The dual serial cost-sharing rule. *Mathematical Social Sciences*, 53(2):150–163, 2007.
- Braden R Allenby, Deanna J Richards, et al. *The greening of industrial ecosystems*. National Academies, 1994.
- Viknesh Andiappan, Raymond R Tan, and Denny KS Ng. An optimization-based negotiation framework for energy systems in an eco-industrial park. *Journal of cleaner production*, 129:496–507, 2016.
- Clinton J Andrews. Building a micro foundation for industrial ecology. *Journal of Industrial Ecology*, 4(3):35–51, 2000.
- Weslyne Ashton. Understanding the organization of industrial ecosystems: A social network approach. *Journal of Industrial Ecology*, 12(1):34–51, 2008.
- Weslyne S Ashton. The structure, function, and evolution of a regional industrial ecosystem. *Journal of Industrial ecology*, 13(2):228–246, 2009.
- Weslyne S Ashton and Ariana C Bain. Assessing the "short mental distance" in eco-industrial networks. *Journal of Industrial Ecology*, 16(1):70–82, 2012.
- Robert J Aumann. *Lectures on game theory*. Westview Pr, 1989.
- Robert J Aumann and Jacques H Dreze. Cooperative games with coalition structures. *International Journal of game theory*, 3(4):217–237, 1974.
- Kathleen B Aviso. Design of robust water exchange networks for eco-industrial symbiosis. *Process Safety and Environmental Protection*, 92(2):160–170, 2014.

- Robert U Ayres, Leslie W Ayres, et al. Industrial ecology. *Books*, 1996.
- Leo W Baas and Frank A Boons. An industrial ecology project in practice: exploring the boundaries of decision-making levels in regional industrial systems. *Journal of Cleaner Production*, 12(8-10):1073–1085, 2004.
- Leo W Baas and Don Huisingsh. The synergistic role of embeddedness and capabilities in industrial symbiosis: illustration based upon 12 years of experiences in the rotterdam harbour and industry complex. *Progress in Industrial Ecology, an International Journal*, 5(5-6):399–421, 2008.
- Reid Bailey, Janet K Allen, and Bert Bras. Applying ecological input-output flow analysis to material flows in industrial systems: Part i: Tracing flows. *Journal of Industrial Ecology*, 8(1-2):45–68, 2004.
- George Baker, Robert Gibbons, and Kevin J Murphy. Relational contracts and the theory of the firm. *The Quarterly Journal of Economics*, 117(1): 39–84, 2002.
- Dia Bandaly, Ahmet Satir, and Latha Shanker. Impact of lead time variability in supply chain risk management. *International Journal of Production Economics*, 180:88–100, 2016.
- Pratima Bansal and Brent McKnight. Looking forward, pushing back and peering sideways: Analyzing the sustainability of industrial symbiosis. *Journal of Supply Chain Management*, 45(4):26–37, 2009.
- Yehuda Bassok and Ravi Anupindi. Analysis of supply contracts with commitments and flexibility. *Naval Research Logistics (NRL)*, 55(5):459–477, 2008.

- David F Batten. Fostering industrial symbiosis with agent-based simulation and participatory modeling. *Journal of Industrial Ecology*, 13(2):197–213, 2009.
- Shishir Kumar Behera, Jung-Hoon Kim, Sang-Yoon Lee, Sangwon Suh, and Hung-Suck Park. Evolution of 'designed' industrial symbiosis networks in the ulsan eco-industrial park: 'research and development into business' as the enabling framework. *Journal of Cleaner Production*, 29:103–112, 2012.
- Nicola Bellantuono, Nunzia Carbonara, and Pierpaolo Pontrandolfo. The organization of eco-industrial parks and their sustainable practices. *Journal of Cleaner Production*, 161:362–375, 2017.
- Rene Van Berkel, Tsuyoshi Fujita, Shizuka Hashimoto, and Minoru Fujii. Quantitative assessment of urban and industrial symbiosis in kawasaki, japan, 2009.
- N Bichraoui, B Guillaume, and A Halog. Agent-based modelling simulation for the development of an industrial symbiosis-preliminary results. *Procedia Environmental Sciences*, 17:195–204, 2013.
- Marianne Boix, Ludovic Montastruc, Luc Pibouleau, Catherine Azzaro-Pantel, and Serge Domenech. Industrial water management by multiobjective optimization: from individual to collective solution through eco-industrial parks. *Journal of Cleaner Production*, 22(1):85–97, 2012.
- Marianne Boix, Ludovic Montastruc, Catherine Azzaro-Pantel, and Serge Domenech. Optimization methods applied to the design of eco-industrial parks: a literature review. *Journal of Cleaner Production*, 87:303–317, 2015.

- FAA Boons and Leo W Baas. Types of industrial ecology: the problem of coordination. *Journal of cleaner production*, 5(1-2):79–86, 1997.
- Frank Boons and Jennifer A Howard-Grenville. *The social embeddedness of industrial ecology*. Edward Elgar Publishing, 2009.
- Frank Boons, Wouter Spekkink, and Yannis Mouzakitidis. The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production*, 19(9-10): 905–911, 2011.
- Frank Boons, Marian Chertow, Jooyoung Park, Wouter Spekkink, and Han Shi. Industrial symbiosis dynamics and the problem of equivalence: Proposal for a comparative framework. *Journal of Industrial Ecology*, 21(4): 938–952, 2017.
- A Bory, F Brevers, C Dopagne, E Droeven, and C van der Kaa. Theme 1a eco-zoning. 2010.
- Adam Brandenburger. Cooperative game theory: Characteristic functions, allocations, marginal contribution. *Stern School of Business. New York University*, 4(1):1–9, 2007.
- Adam Brandenburger and Harborne Stuart. Biform games. *Management science*, 53(4):537–549, 2007.
- Robin Branson. Re-constructing kalundborg: the reality of bilateral symbiosis and other insights. *Journal of Cleaner Production*, 112:4344–4352, 2016.
- Sabrina Brulot, Muriel Maillefert, and Jérémie Joubert. Stratégies d’acteurs et gouvernance des démarches d’écologie industrielle et territori-

- ale. *Développement durable et territoires. Économie, géographie, politique, droit, sociologie*, 5(1), 2014.
- Arnt Buvik and Torger Reve. Asymmetrical deployment of specific assets and contractual safeguarding in industrial purchasing relationships. *Journal of Business Research*, 51(2):101–113, 2001.
- Gérard P Cachon. Supply chain coordination with contracts. *Handbooks in operations research and management science*, 11:227–339, 2003.
- Franjo Cecelja, T Raafat, N Trokanas, S Innes, M Smith, A Yang, Y Zorgios, A Korkofygas, and Antonis Kokossis. e-symbiosis: technology-enabled support for industrial symbiosis targeting small and medium enterprises and innovation. *Journal of Cleaner Production*, 98:336–352, 2015.
- Song Hwa Chae, Sang Hun Kim, Sung-Geun Yoon, and Sunwon Park. Optimization of a waste heat utilization network in an eco-industrial park. *Applied Energy*, 87(6):1978–1988, 2010.
- Alain Chauvel, Gilles Fournier, and Claude Raimbault. *Manuel d'évaluation économique des procédés*. Editions Technip, 2001.
- Yeon-Koo Che and Donald B Hausch. Cooperative investments and the value of contracting. *American Economic Review*, 89(1):125–147, 1999.
- Marian Chertow and John Ehrenfeld. Organizing self-organizing systems: Toward a theory of industrial symbiosis. *Journal of Industrial Ecology*, 16(1):13–27, 2012.
- Marian R Chertow. Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment*, 25(1):313–337, 2000.

- Marian R Chertow. "uncovering" industrial symbiosis. *Journal of Industrial Ecology*, 11(1):11–30, 2007.
- Marian R Chertow and Weslynn S Ashton. The social embeddedness of industrial symbiosis linkages in puerto rican industrial regions. *The social embeddedness of industrial ecology*, pages 128–151, 2009.
- Irene Mei Leng Chew, Raymond R Tan, Dominic Chwan Yee Foo, and Anthony Shun Fung Chiu. Game theory approach to the analysis of inter-plant water integration in an eco-industrial park. *Journal of Cleaner Production*, 17(18):1611–1619, 2009.
- Irene Mei Leng Chew, Sinthi Laya Thillaivarrna, Raymond R Tan, and Dominic Chwan Yee Foo. Analysis of inter-plant water integration with indirect integration schemes through game theory approach: Pareto optimal solution with interventions. *Clean Technologies and Environmental Policy*, 13(1):49–62, 2011.
- Shauhrat S Chopra and Vikas Khanna. Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of environmental management*, 141:86–94, 2014.
- Ronald H Coase. The nature of the firm. *economica*, 4(16):386–405, 1937.
- Antonio Colmenar-Santos, Enrique Rosales-Asensio, David Borge-Diez, and Francisco Mur-Pérez. Cogeneration and district heating networks: Measures to remove institutional and financial barriers that restrict their joint use in the eu-28. *Energy*, 85:403–414, 2015.
- Ian A Cooper and Sergei A Davydenko. The cost of debt. 2001.

- Inês Costa and Paulo Ferrão. A case study of industrial symbiosis development using a middle-out approach. *Journal of Cleaner Production*, 18 (10-11):984–992, 2010.
- JR Couper, DW Hartz, and FL Smith. Process economics.-section 9.-53 p. in «perry's chemical engineer's handbook», 2008.
- Morton Davis and Michael Maschler. The kernel of a cooperative game. *Naval Research Logistics Quarterly*, 12(3):223–259, 1965.
- Pierre Desrochers. Industrial ecology and the rediscovery of inter-firm recycling linkages: historical evidence and policy implications. *Industrial and Corporate Change*, 11(5):1031–1057, 2002.
- Pauline Deutz and David Gibbs. Industrial ecology and regional development: eco-industrial development as cluster policy. *Regional Studies*, 42 (10):1313–1328, 2008.
- Teresa Domenech and Michael Davies. Structure and morphology of industrial symbiosis networks: The case of kalundborg. *Procedia-Social and Behavioral Sciences*, 10:79–89, 2011.
- John Ehrenfeld. Industrial ecology: a new field or only a metaphor? *Journal of cleaner production*, 12(8-10):825–831, 2004.
- Stanil Y Ereev and Martin K Patel. Standardized cost estimation for new technology (scent)-methodology and tool. *Journal of Business Chemistry*, pages 31–48, 2012.
- Michael Essig. Purchasing consortia as symbiotic relationships: developing the concept of "consortium sourcing". *European Journal of Purchasing & Supply Management*, 6(1):13–22, 2000.

- Romain Farel, Benoît Charrière, Charlotte Thevenet, and Jeremy H Yune. Sustainable manufacturing through creation and governance of eco-industrial parks. *Journal of Manufacturing Science and Engineering*, 138(10):101003, 2016.
- LM Farrell. Principal-agency risk in project finance. *International Journal of Project Management*, 21(8):547–561, 2003.
- M Gloria Fiestras-Janeiro, Ignacio García-Jurado, Ana Meca, and Manuel A Mosquera. Cooperative game theory and inventory management. *European Journal of Operational Research*, 210(3):459–466, 2011.
- Luca Fraccascia, Ilaria Giannoccaro, and Vito Albino. Efficacy of landfill tax and subsidy policies for the emergence of industrial symbiosis networks: an agent-based simulation study. *Sustainability*, 9(4):521, 2017.
- Eric Friedman and Herve Moulin. Three methods to share joint costs or surplus. *Journal of economic Theory*, 87(2):275–312, 1999.
- Robert A Frosch and Nicholas E Gallopoulos. Towards an industrial ecology. *The treatment and handling of wastes*, pages 269–292, 1992.
- Martin Geissdoerfer, Paulo Savaget, Nancy MP Bocken, and Erik Jan Hultink. The circular economy—a new sustainability paradigm? *Journal of Cleaner Production*, 143:757–768, 2017.
- Yong Geng, Zuoxi Liu, Bing Xue, Huijuan Dong, Tsuyoshi Fujita, and Anthony Chiu. Emergy-based assessment on industrial symbiosis: a case of shenyang economic and technological development zone. *Environmental Science and Pollution Research*, 21(23):13572–13587, 2014.

- Robert Gibbons and Rebecca Henderson. Relational contracts and organizational capabilities. *Organization Science*, 23(5):1350–1364, 2012.
- David Gibbs and Pauline Deutz. Implementing industrial ecology? planning for eco-industrial parks in the usa. *Geoforum*, 36(4):452–464, 2005.
- Donald B Gillies. Solutions to general non-zero-sum games. *Contributions to the Theory of Games*, 4(40):47–85, 1959.
- Artem Golev, Glen D Corder, and Damien P Giurco. Industrial symbiosis in gladstone: A decade of progress and future development. *Journal of cleaner production*, 84:421–429, 2014.
- Alejandra Gomez-Padilla, Jeanne Duvallet, and Daniel Llerena. Contract typology as a research method in supply chain management. In *Research Methodologies in Supply Chain Management*, pages 525–538. Springer, 2005.
- Kannan Govindan, Maria Nicoleta Popiuc, and Ali Diabat. Overview of coordination contracts within forward and reverse supply chains. *Journal of Cleaner Production*, 47:319–334, 2013.
- Michel Grabisch and Yukihiro Funaki. A coalition formation value for games in partition function form. *European Journal of Operational Research*, 221(1):175–185, 2012.
- Gene M Grossman and Alan B Krueger. Economic growth and the environment. *The quarterly journal of economics*, 110(2):353–377, 1995.
- Sanford J Grossman and Oliver D Hart. The costs and benefits of ownership: A theory of vertical and lateral integration. *Journal of political economy*, 94(4):691–719, 1986.

- Anupam Gupta, Aravind Srinivasan, and Éva Tardos. Cost-sharing mechanisms for network design. *Algorithmica*, 50(1):98–119, 2008.
- Roman Hackl and Simon Harvey. Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters. *Applied energy*, 112:1500–1509, 2013.
- EM Harper and TE Graedel. Industrial ecology: a teenager’s progress. *Technology in Society*, 26(2-3):433–445, 2004.
- Oliver Hart and John Moore. Incomplete contracts and renegotiation. *Econometrica: Journal of the Econometric Society*, pages 755–785, 1988.
- Shizuka Hashimoto, Tsuyoshi Fujita, Yong Geng, and Emiri Nagasawa. Realizing co2 emission reduction through industrial symbiosis: a cement production case study for kawasaki. *Resources, Conservation and Recycling*, 54(10):704–710, 2010.
- Saeid Hatefipour, Leenard Baas, and Mats Eklund. The händelö area in norrköping; sweden. does it fit for industrial symbiosis development? In *World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden*, number 057, pages 3468–3475. Linköping University Electronic Press, 2011.
- RR Heeres, Walter JV Vermeulen, and FB De Walle. Eco-industrial park initiatives in the usa and the netherlands: first lessons. *Journal of cleaner production*, 12(8-10):985–995, 2004.
- Anna-Mari Heikkilä, Yngve Malmén, Minna Nissilä, and Helena Kortelainen. Challenges in risk management in multi-company industrial parks. *Safety science*, 48(4):430–435, 2010.

- Andreas M Hein, Marija Jankovic, Romain Farel, and Bernard Yannou. A data-and knowledge-driven methodology for generating eco-industrial park architectures. In *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages V004T05A002–V004T05A002. American Society of Mechanical Engineers, 2016.
- Andreas M Hein, Marija Jankovic, Wen Feng, Romain Farel, Jeremy H Yune, and Bernard Yannou. Stakeholder power in industrial symbioses: A stakeholder value network approach. *Journal of cleaner production*, 148:923–933, 2017.
- R Glenn Hubbard and Robert J Weiner. Regulation and long-term contracting in us natural gas markets. *The Journal of Industrial Economics*, pages 71–79, 1986.
- NX Jia and R Yokoyama. Profit allocation of independent power producers based on cooperative game theory. *International journal of electrical power & energy systems*, 25(8):633–641, 2003.
- Wenting Jiao and Frank Boons. Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production*, 67:14–25, 2014.
- Florian Julien-Saint-Amand and Patricia Le Moenner. Industrial ecology, an innovative approach serving spatial planning: the example of the tool presteo©(a program to research synergies on a territory). In *6th International Conference of Territorial Intelligence" Tools and methods of Territorial Intelligence"*, Besançon, 2008, 2008.

- Ehud Kalai and Meir Smorodinsky. Other solutions to nash's bargaining problem. *Econometrica: Journal of the Econometric Society*, pages 513–518, 1975.
- Frank Karsten and Rob JI Basten. Pooling of spare parts between multiple users: How to share the benefits? *European journal of operational research*, 233(1):94–104, 2014.
- Catharine A Kastner, Raymond Lau, and Markus Kraft. Quantitative tools for cultivating symbiosis in industrial parks; a literature review. *Applied Energy*, 155:599–612, 2015.
- Julian Kirchherr, Denise Reike, and Marko Hekkert. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127:221–232, 2017.
- Bruce Kogut. Joint ventures: Theoretical and empirical perspectives. *Strategic management journal*, 9(4):319–332, 1988.
- Srinivas Sahan Kolluri, Iman Janghorban Esfahani, and ChangKyoo Yoo. Robust fuzzy and multi-objective optimization approaches to generate alternate solutions for resource conservation of eco-industrial park involving various future events. *Process Safety and Environmental Protection*, 103:424–441, 2016.
- Jouni Korhonen. Co-production of heat and power: an anchor tenant of a regional industrial ecosystem. *Journal of Cleaner Production*, 9(6):509–517, 2001a.
- Jouni Korhonen. Some suggestions for regional industrial ecosystems—extended industrial ecology. *Eco-Management and Auditing: The Journal of Corporate Environmental Management*, 8(1):57–69, 2001b.

- Jouni Korhonen and Juha-Pekka Snäkin. Analysing the evolution of industrial ecosystems: concepts and application. *Ecological Economics*, 52(2): 169–186, 2005.
- E Kuznetsova and Enrico Zio. Development of a case study for eco-industrial park deployment under uncertainty. In *ESREL 2015*, 2015.
- Elizaveta Kuznetsova, Rim Louhichi, Enrico Zio, and Romain Farel. Input-output inoperability model for the risk analysis of eco-industrial parks. *Journal of Cleaner Production*, 164:779–792, 2017.
- JJ Laffont and David Martimort. The theory of incentives, princeton univ, 2002.
- Gunter Lay, Marcus Schroeter, and Sabine Biege. Service-based business concepts: A typology for business-to-business markets. *European Management Journal*, 27(6):442–455, 2009.
- Suvi Lehtoranta, Ari Nissinen, Tuomas Mattila, and Matti Melanen. Industrial symbiosis and the policy instruments of sustainable consumption and production. *Journal of Cleaner Production*, 19(16):1865–1875, 2011.
- Yik Teeng Leong, Jui-Yuan Lee, Raymond R Tan, Ji Jinn Foo, and Irene Mei Leng Chew. Multi-objective optimization for resource network synthesis in eco-industrial parks using an integrated analytic hierarchy process. *Journal of cleaner production*, 143:1268–1283, 2017.
- Delberis A Lima, Javier Contreras, and Antonio Padilha-Feltrin. A cooperative game theory analysis for transmission loss allocation. *Electric Power Systems Research*, 78(2):264–275, 2008.

- Ewa Liwarska-Bizukoje, Marcin Bizukoje, Andrzej Marcinkowski, and Andrzej Doniec. The conceptual model of an eco-industrial park based upon ecological relationships. *Journal of Cleaner Production*, 17(8):732–741, 2009.
- D Rachel Lombardi and Peter Laybourn. Redefining industrial symbiosis: Crossing academic–practitioner boundaries. *Journal of Industrial Ecology*, 16(1):28–37, 2012.
- Jesús María López-Lezama, Antonio Padilha-Feltrin, Javier Contreras, and José Ignacio Muñoz. Optimal contract pricing of distributed generation in distribution networks. *IEEE Transactions on Power Systems*, 26(1):128–136, 2011.
- Eva M Lovelady and Mahmoud M El-Halwagi. Design and integration of eco-industrial parks for managing water resources. *Environmental Progress & Sustainable Energy: An Official Publication of the American Institute of Chemical Engineers*, 28(2):265–272, 2009.
- Ernest A Lowe. Creating by-product resource exchanges: strategies for eco-industrial parks. *Journal of cleaner production*, 5(1-2):57–65, 1997.
- Ernest A Lowe. Eco-industrial park handbook for asian developing countries. *Report to Asian Development Bank*, 2001.
- Ernest A Lowe and Laurence K Evans. Industrial ecology and industrial ecosystems. *Journal of cleaner production*, 3(1-2):47–53, 1995.
- Yashar Maali. A multiobjective approach for solving cooperative n-person games. *International Journal of Electrical Power & Energy Systems*, 31(10):608–610, 2009.

- Eric Maskin and Jean Tirole. Unforeseen contingencies and incomplete contracts. *The Review of Economic Studies*, 66(1):83–114, 1999.
- Guillaume Massard and Suren Erkman. A regional industrial symbiosis methodology and its implementation in geneva, switzerland. In *3rd International Conference on Life Cycle Management. Irchel: University of Zurich*, 2007.
- Guillaume Massard, Olivier Jacquat, and Daniel Zürcher. International survey on ecoinnovation parks. In *Workshop on eco-innovation parks*, volume 20, page 12, 2014.
- Scott E Masten. Minimum bill contracts: Theory and policy. *The Journal of Industrial Economics*, pages 85–97, 1988.
- Puneet Prakash Mathur and Janat Shah. Supply chain contracts with capacity investment decision: Two-way penalties for coordination. *International journal of production economics*, 114(1):56–70, 2008.
- S Peters Max, D Timmerhaus Klaus, and E West Ronald. Plant design and economics for chemical engineers. *International edition*, 1991.
- Andrew McCarthy, Rob Dellink, Ruben Bibas, et al. The macroeconomics of the circular economy transition: A critical review of modelling approaches. Technical report, OECD Publishing, 2018.
- William McDonough and Michael Braungart. *Cradle to cradle: Remaking the way we make things*. North point press, 2010.
- Donella H Meadows, Donella H Meadows, Jørgen Randers, and William W Behrens III. The limits to growth: a report to the club of rome (1972). *Google Scholar*, 1972.

- Claude Ménard. Hybrid modes of organization. alliances, joint ventures, networks, and other 'strange' animals, 2012.
- Murat Mirata and Tareq Emtairah. Industrial symbiosis networks and the contribution to environmental innovation: the case of the landskrona industrial symbiosis programme. *Journal of cleaner production*, 13(10-11): 993–1002, 2005.
- Robin Molinier. Capacity choices under uncertainty for infrastructure sharing synergies: a robust optimization formulation. In *1 st International Conference on Energy Engineering and Smart Grids*, 2018a.
- Robin Molinier. Infrastructure sharing synergies: strategic capacity setting under uncertainty. In *41 st IAEE International Conference*, 2018b.
- Robin Molinier and Pascal Da Costa. Infrastructure sharing synergies and industrial symbiosis: optimal capacity oversizing and pricing. *Journal of Industrial and Intelligent Information*, in Press.
- Robin Molinier and Elisabeth LeNet. L'écologie industrielle comme nouveau business model des filières bois-papier, le cas de green valley. *ENTRE DYNAMIQUES ET MUTATIONS, QUELLES VOIES POUR LA FORET ET LE BOIS?*, 2018.
- Max Monauni. Agility enablers in production networks—pooling and allying of manufacturing resources. *Procedia CIRP*, 17:657–662, 2014.
- Ludovic Montastruc, Marianne Boix, Luc Pibouleau, Catherine Azzaro-Pantel, and Serge Domenech. On the flexibility of an eco-industrial park (eip) for managing industrial water. *Journal of cleaner production*, 43: 1–11, 2013.

- Oskar Morgenstern and John Von Neumann. *Theory of games and economic behavior*. Princeton university press, 1953.
- Herve Moulin and Scott Shenker. Serial cost sharing. *Econometrica: Journal of the Econometric Society*, pages 1009–1037, 1992.
- Hervé Moulin and Scott Shenker. Strategyproof sharing of submodular costs: budget balance versus efficiency. *Economic Theory*, 18(3):511–533, 2001.
- Roger B Myerson. Values of games in partition function form. *International Journal of Game Theory*, 6(1):23–31, 1977.
- John F Nash Jr. The bargaining problem. *Econometrica: Journal of the Econometric Society*, pages 155–162, 1950.
- Georg Nöldeke and Klaus M Schmidt. Option contracts and renegotiation: a solution to the hold-up problem. *The RAND Journal of Economics*, pages 163–179, 1995.
- Oree. Le recueil des demarches d’ecologie industrielle et territoriale. Technical report, Oree, 2016.
- Suvi Pakarinen, Tuomas Mattila, Matti Melanen, Ari Nissinen, and Laura Sokka. Sustainability and industrial symbiosis-the evolution of a finnish forest industry complex. *Resources, Conservation and Recycling*, 54(12): 1393–1404, 2010.
- Ming Pan, Janusz Sikorski, Jethro Akroyd, Sebastian Mosbach, Raymond Lau, and Markus Kraft. Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks. *Applied Energy*, 175:305–323, 2016.

- Raymond L Paquin, Timo Busch, and Suzanne G Tilleman. Creating economic and environmental value through industrial symbiosis. *Long Range Planning*, 48(2):95–107, 2015.
- Hung-Suck Park and Shishir Kumar Behera. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. *Journal of Cleaner Production*, 64:478–485, 2014.
- Samuli Patala, Sari Hämäläinen, Anne Jalkala, and Hanna-Leena Pesonen. Towards a broader perspective on the forms of eco-industrial networks. *Journal of cleaner production*, 82:166–178, 2014.
- Pieter H Pellenburg. Sustainable business sites in the netherlands: a survey of policies and experiences. *Journal of Environmental Planning and Management*, 45(1):59–84, 2002.
- Laura Poppo and Todd Zenger. Do formal contracts and relational governance function as substitutes or complements? *Strategic management journal*, 23(8):707–725, 2002.
- Xuan Qiu and George Q Huang. Supply hub in industrial park (ship): The value of freight consolidation. *Computers & industrial engineering*, 65(1):16–27, 2013.
- Gilles Reinhardt and Maqbool Dada. Allocating the gains from resource pooling with the shapley value. *Journal of the Operational Research Society*, 56(8):997–1000, 2005.
- Brian H Roberts. The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an australian case study. *Journal of cleaner production*, 12(8-10):997–1010, 2004.

- Elena Romero and M Carmen Ruiz. Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems. *Science of the Total Environment*, 468:394–405, 2014.
- Ariel Rubinstein. Perfect equilibrium in a bargaining model. *Econometrica: Journal of the Econometric Society*, pages 97–109, 1982.
- Frank Schiller, Alexandra S Penn, and Lauren Basson. Analyzing networks in industrial ecology—a review of social-material network analyses. *Journal of Cleaner Production*, 76:1–11, 2014.
- Edella Schlager and Elinor Ostrom. Property-rights regimes and natural resources: a conceptual analysis. *Land economics*, pages 249–262, 1992.
- David Schmeidler. The nucleolus of a characteristic function game. *SIAM Journal on applied mathematics*, 17(6):1163–1170, 1969.
- Cristina Sendra, Xavier Gabarrell, and Teresa Vicent. Material flow analysis adapted to an industrial area. *Journal of Cleaner Production*, 15(17):1706–1715, 2007.
- Dogan A Serel. Capacity reservation under supply uncertainty. *Computers & Operations Research*, 34(4):1192–1220, 2007.
- Lloyd S Shapley. A value for n-person games. *Contributions to the Theory of Games*, 2(28):307–317, 1953.
- Zunya Shi, Nengmin Wang, Tao Jia, and Haoxun Chen. Reverse revenue sharing contract versus two-part tariff contract under a closed-loop supply chain system. *Mathematical Problems in Engineering*, 2016, 2016.

- Thomas Sikor, Jun He, and Guillaume Lestrelin. Property rights regimes and natural resources: a conceptual analysis revisited. *World Development*, 93: 337–349, 2017.
- Wouter Spekkink. Institutional capacity building for industrial symbiosis in the canal zone of zeeland in the netherlands: A process analysis. *Journal of cleaner production*, 52:342–355, 2013.
- Stefan Spinler and Arnd Huchzermeier. The valuation of options on capacity with cost and demand uncertainty. *European Journal of Operational Research*, 171(3):915–934, 2006.
- Thomas Sterr and Thomas Ott. The industrial region as a promising unit for eco-industrial development-reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production*, 12(8-10):947–965, 2004.
- Li Sun, Wouter Spekkink, Eefje Cuppen, and Gijsbert Korevaar. Coordination of industrial symbiosis through anchoring. *Sustainability*, 9(4):549, 2017.
- Raymond R Tan, Viknesh Andiappan, Yoke Kin Wan, Rex TL Ng, and Denny KS Ng. An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration. *Chemical Engineering Research and Design*, 106:43–58, 2016.
- Kai Yuan Teo, Tze Yee Ng, Cze Min Wau, Jason TS Liew, Viknesh Andiappan, and Denny KS Ng. Hybrid optimisation model for the synthesis of centralised utility system in eco-industrial park. *Process Integration and Optimization for Sustainability*, 1(1):33–57, 2017.

- Maryline Thénot and Katir Honorine. La bioéconomie industrielle à l'échelle d'une région: la bioraffinerie de bazancourt-pomacle, tremplin d'une stratégie territoriale. In *Annales des Mines-Réalités industrielles*, number 1, pages 66–70. FFE, 2017.
- Robert M Thrall and William F Lucas. N-person games in partition function form. *Naval Research Logistics Quarterly*, 10(1):281–298, 1963.
- Ronald S Tibben-Lembke. N-period contracts with ordering constraints and total minimum commitments: optimal and heuristic solutions. *European Journal of Operational Research*, 156(2):353–374, 2004.
- Bryan Timothy C Tiu and Dennis E Cruz. An milp model for optimizing water exchanges in eco-industrial parks considering water quality. *Resources, Conservation and Recycling*, 119:89–96, 2017.
- Takuya Togawa, Tsuyoshi Fujita, Liang Dong, Minoru Fujii, and Makoto Ooba. Feasibility assessment of the use of power plant-sourced waste heat for plant factory heating considering spatial configuration. *Journal of cleaner production*, 81:60–69, 2014.
- Eric WK Tsang. Transaction cost and resource-based explanations of joint ventures: A comparison and synthesis. *Organization studies*, 21(1):215–242, 2000.
- Andy A Tsay and William S Lovejoy. Quantity flexibility contracts and supply chain performance. *Manufacturing & Service Operations Management*, 1(2):89–111, 1999.
- Terry Tudor, Emma Adam, and Margaret Bates. Drivers and limitations for the successful development and functioning of eips (eco-industrial parks): A literature review. *Ecological Economics*, 61(2-3):199–207, 2007.

- Arnold Tukker. Eight types of product–service system: eight ways to sustainability? experiences from suspronet. *Business strategy and the environment*, 13(4):246–260, 2004.
- Aristotle T Ubando, Alvin B Culaba, Kathleen B Aviso, Raymond R Tan, Joel L Cuello, Denny KS Ng, and Mahmoud M El-Halwagi. Fuzzy mixed integer non-linear programming model for the design of an algae-based eco-industrial park with prospective selection of support tenants under product price variability. *Journal of cleaner production*, 136:183–196, 2016.
- Guillermo Valenzuela-Venegas, J Cristian Salgado, and Felipe A Díaz-Alvarado. Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. *Journal of cleaner production*, 133:99–116, 2016.
- Dick Van Beers, Albena Bossilkov, Glen Corder, and Rene Van Berkel. Industrial symbiosis in the australian minerals industry: the cases of kwinana and gladstone. *Journal of Industrial Ecology*, 11(1):55–72, 2007.
- Lilian Bechara Elabras Veiga and Alessandra Magrini. Eco-industrial park development in rio de janeiro, brazil: a tool for sustainable development. *Journal of cleaner production*, 17(7):653–661, 2009.
- Vesela Veleva, Svetlana Todorova, Peter Lowitt, Neil Angus, and Dona Neely. Understanding and addressing business needs and sustainability challenges: lessons from devens eco-industrial park. *Journal of Cleaner Production*, 87:375–384, 2015.
- Judith L Walls and Raymond L Paquin. Organizational perspectives of industrial symbiosis: A review and synthesis. *Organization & Environment*, 28(1):32–53, 2015.

- Oliver E Williamson. Transaction-cost economics: the governance of contractual relations. *The journal of Law and Economics*, 22(2):233–261, 1979.
- Oliver E Williamson. The economics of governance. *American Economic Review*, 95(2):1–18, 2005.
- Dong J Wu, Paul R Kleindorfer, and Jin E Zhang. Optimal bidding and contracting strategies for capital-intensive goods. *European Journal of Operational Research*, 137(3):657–676, 2002.
- Junnian Wu, Yan Guo, Chengliang Li, and Hang Qi. The redundancy of an industrial symbiosis network: A case study of a hazardous waste symbiosis network. *Journal of Cleaner Production*, 149:49–59, 2017.
- Nonita Tumulak Yap and John Fredrick Devlin. Explaining industrial symbiosis emergence, development, and disruption: a multilevel analytical framework. *Journal of industrial Ecology*, 21(1):6–15, 2017.
- Sudhakar Yedla and Hung-Suck Park. Eco-industrial networking for sustainable development: review of issues and development strategies. *Clean Technologies and Environmental Policy*, 19(2):391–402, 2017.
- Chang Yu, Martin de Jong, and Gerard PJ Dijkema. Process analysis of eco-industrial park development—the case of tianjin, china. *Journal of Cleaner Production*, 64:464–477, 2014.
- Amy Z Zeng and Yu Xia. Building a mutually beneficial partnership to ensure backup supply. *Omega*, 52:77–91, 2015.
- Yan Zhang, Hongmei Zheng, Bin Chen, and Naijin Yang. Social network analysis and network connectedness analysis for industrial symbiotic sys-

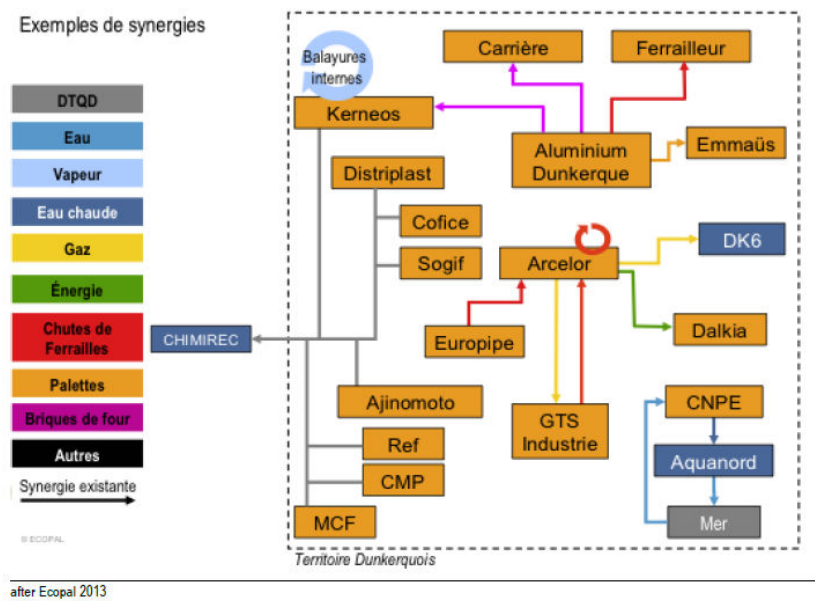
- tems: model development and case study. *Frontiers of Earth Science*, 7(2):169–181, 2013.
- Yan Zhang, Hongmei Zheng, and Brian D Fath. Ecological network analysis of an industrial symbiosis system: a case study of the shandong lubei eco-industrial park. *Ecological Modelling*, 306:174–184, 2015.
- Haoran Zhao, Sen Guo, and Huiru Zhao. Comprehensive benefit evaluation of eco-industrial parks by employing the best-worst method based on circular economy and sustainability. *Environment, Development and Sustainability*, 20(3):1229–1253, 2018a.
- Haoran Zhao, Sen Guo, and Huiru Zhao. Evaluating the comprehensive benefit of eco-industrial parks by employing multi-criteria decision making approach for circular economy. *Journal of Cleaner Production*, 142(142): 2262–2276, 2018b.
- HM Zheng, Y Zhang, and NJ Yang. Evaluation of an eco-industrial park based on a social network analysis. *Procedia Environmental Sciences*, 13: 1624–1629, 2012.
- Junming Zhu and Matthias Ruth. The development of regional collaboration for resource efficiency: A network perspective on industrial symbiosis. *Computers, Environment and Urban Systems*, 44:37–46, 2014.
- Li Zhu, Jianren Zhou, Zhaojie Cui, and Lei Liu. A method for controlling enterprises access to an eco-industrial park. *Science of the total environment*, 408(20):4817–4825, 2010.
- Qinghua Zhu, Ernest A Lowe, Yuan-an WEI, and Donald Barnes. Industrial symbiosis in china: a case study of the guitang group. *Journal of Industrial Ecology*, 11(1):31–42, 2007.

Appendix A

list of EIPs

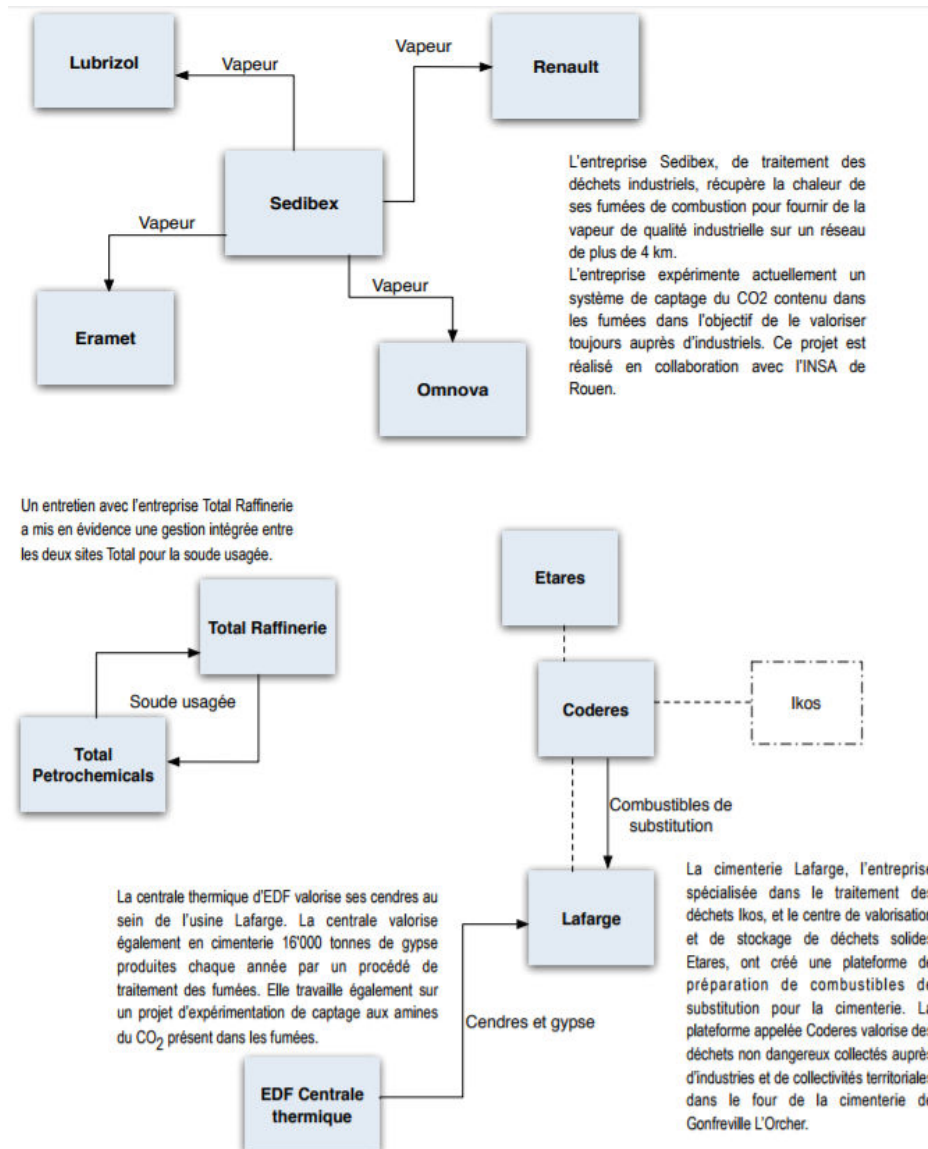
□ Dunkerque, France

Fig. 20 > Industrial symbioses in Dunkerque



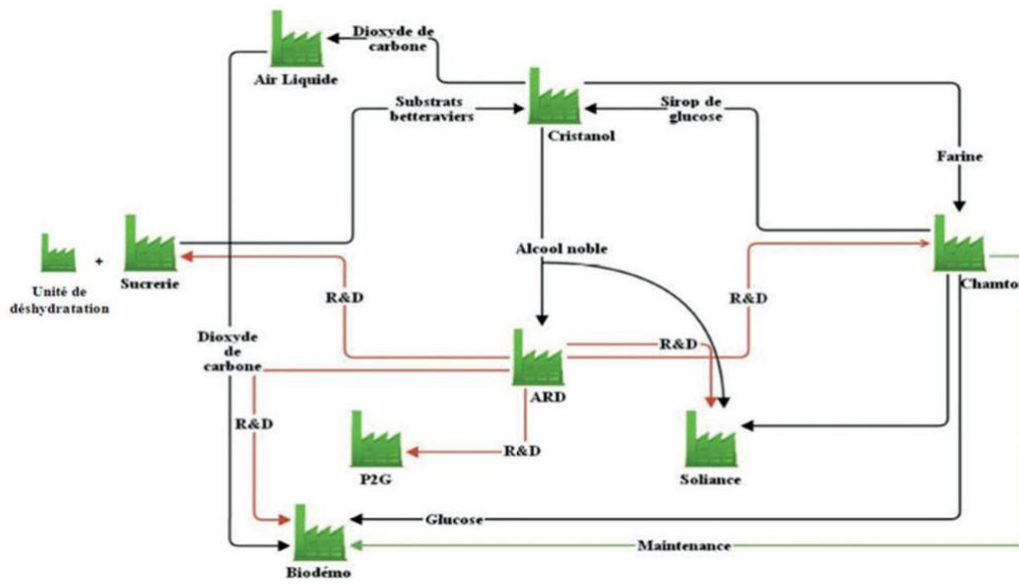
Reference: Oree (2016)

□ Le Havre, France



Reference: Hein et al. (2017)

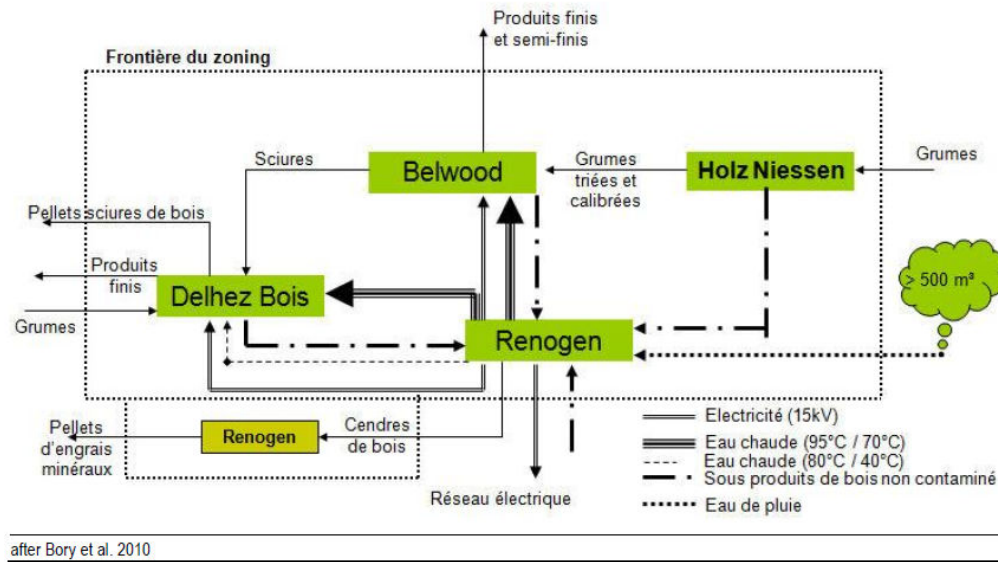
□ Bazancourt-Pomacle, France



Reference: Thénot and Honorine (2017)

□ Kaisersbaracke, Belgium

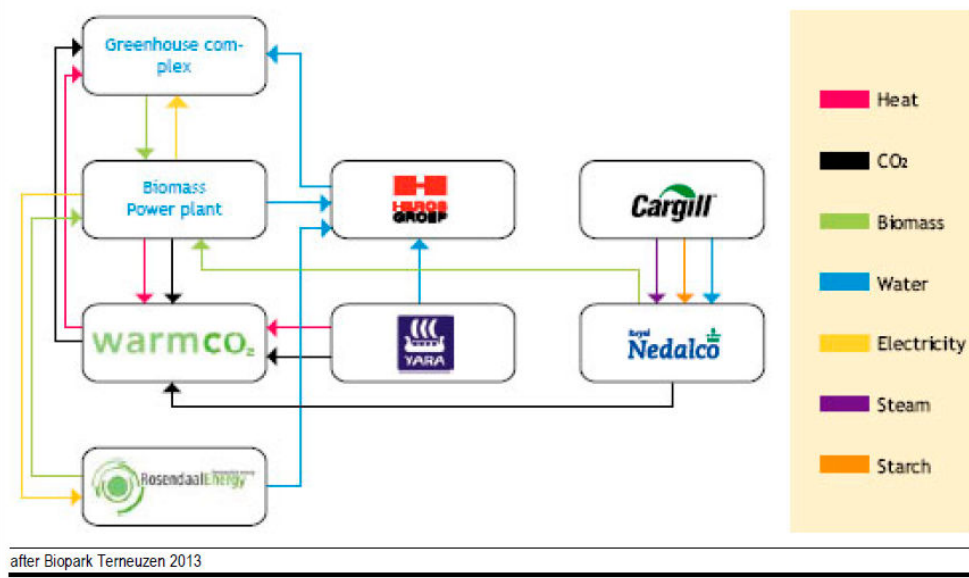
Fig. 14 > Industrial symbioses in Kaisersbaracke



Reference: Bory et al. (2010)

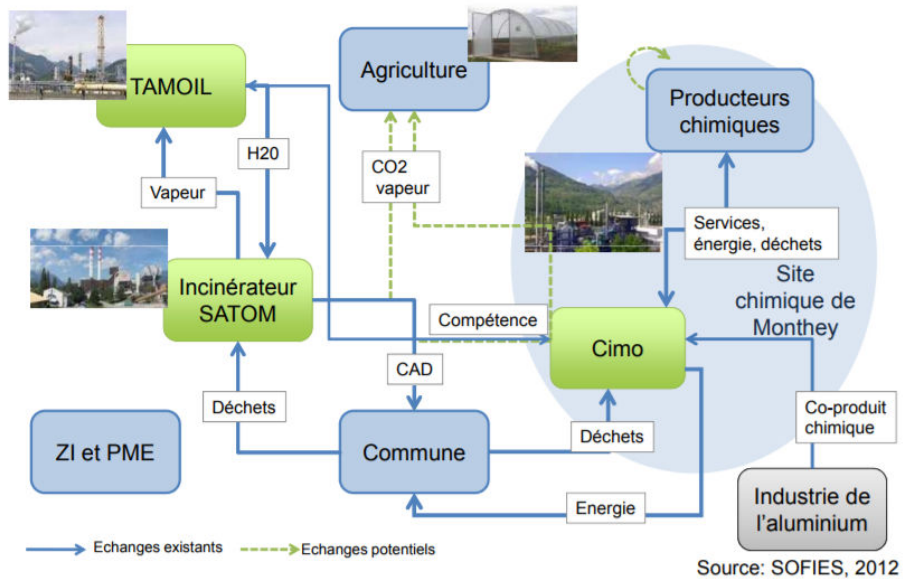
□ Terneusen, Nederlands

Fig. 26 > Smart links in Biopark Terneuzen



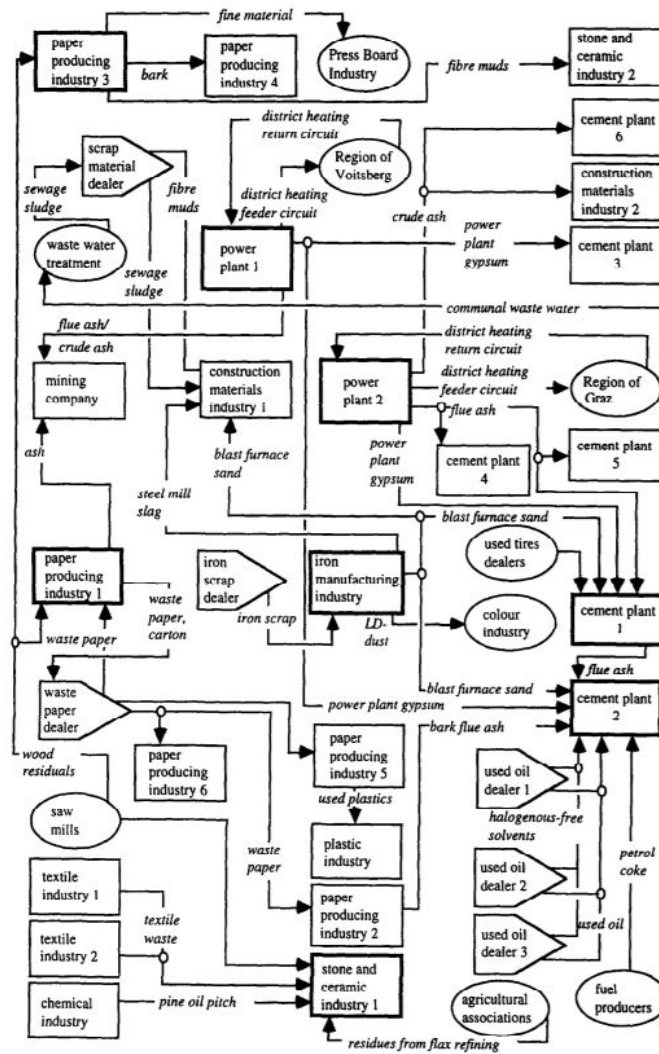
Reference: Spekkink (2013)

□ Monthey-Chablais, Switzerland



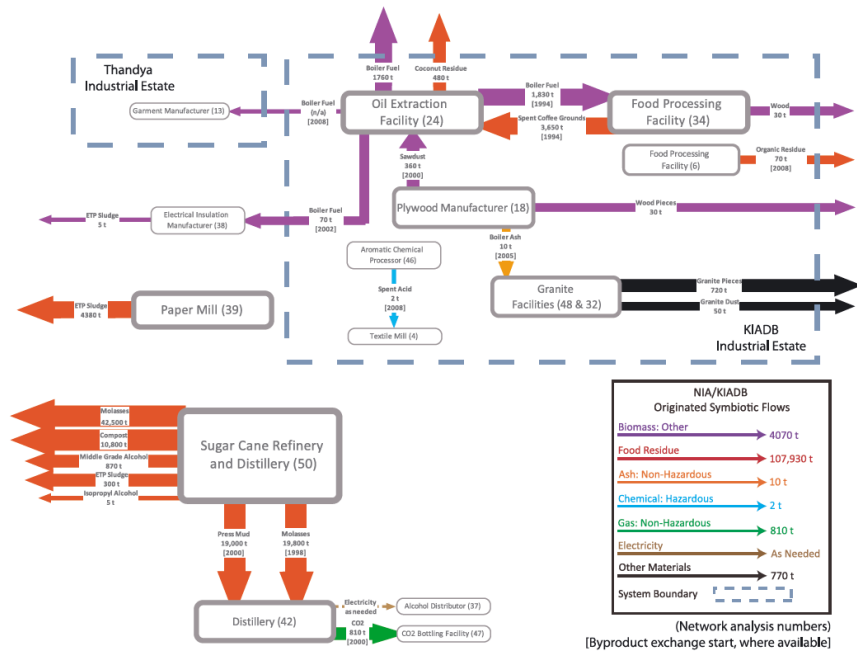
Reference: Massard et al. (2014)

□ Styria, Austria



Reference: Sterr and Ott (2004)

□ Nanjangud, India

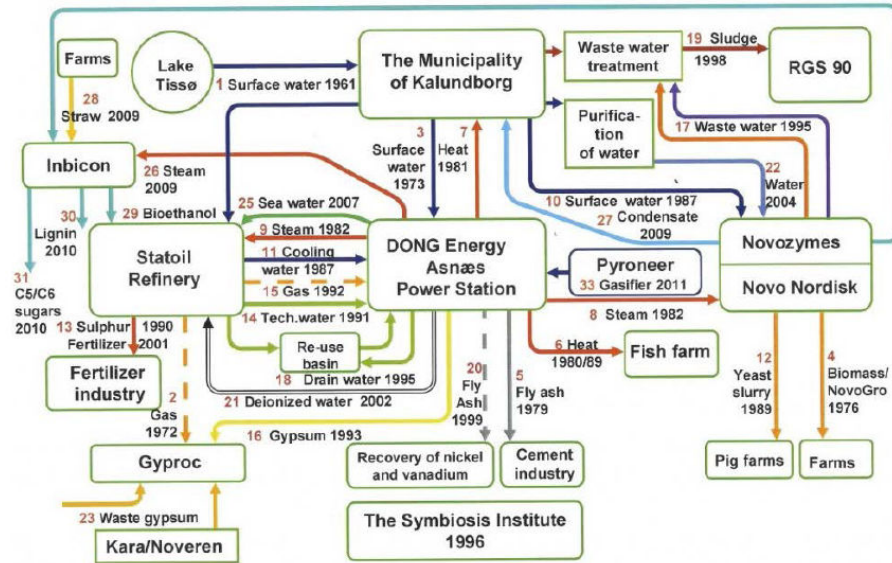


Reference: Ashton and Bain (2012)

□ Kalundborg, Denmark

Fig. 15 > Industrial symbioses in Kalundborg

The residual products traded include steam, dust, gases, heat, slurry, water, gypsum and sludge.

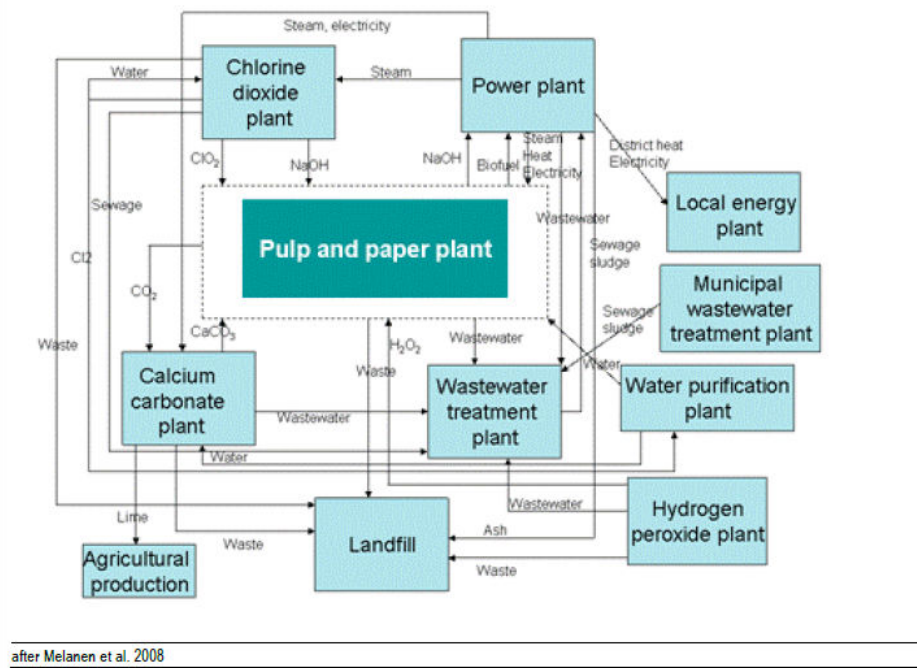


after Kalundborg Symbiosis, 2013

Reference: Chertow (2007)

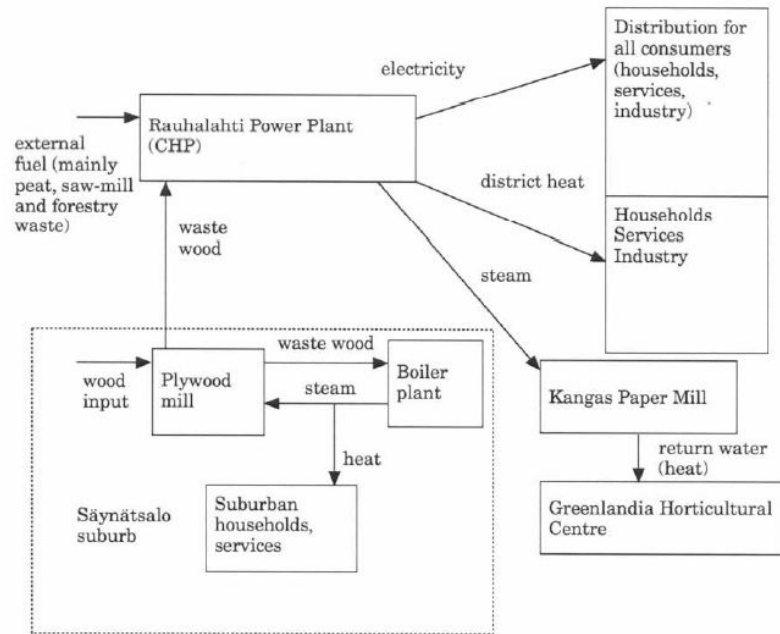
□ Kymi, Finland

Fig. 17 > Kymi EIP material and energy exchanges



Reference: Pakarinen et al. (2010)

□ Jyvaskyla, Finland

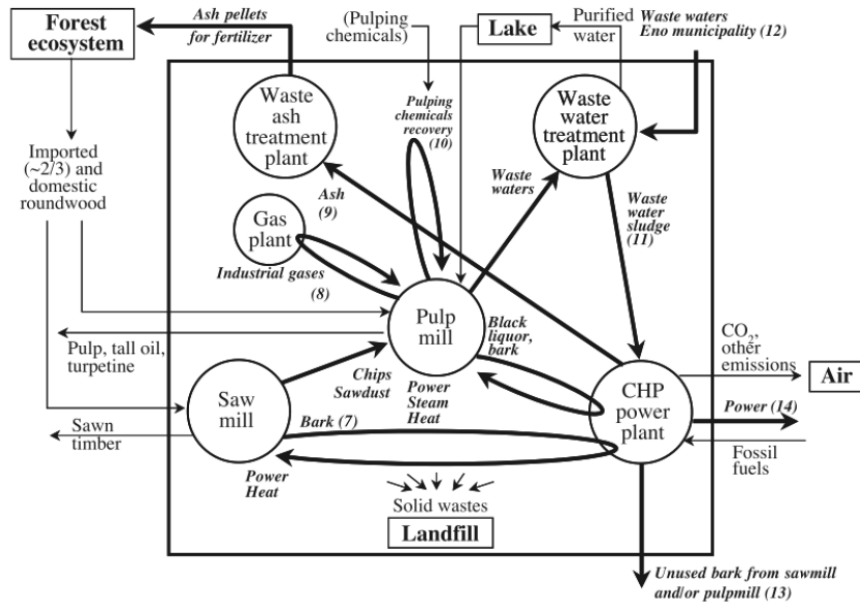


Reference: Korhonen (2001a)

□ Uimaharju, Finland

Fig. 19 > Last stage of industrial ecosystem development in Uimaharju

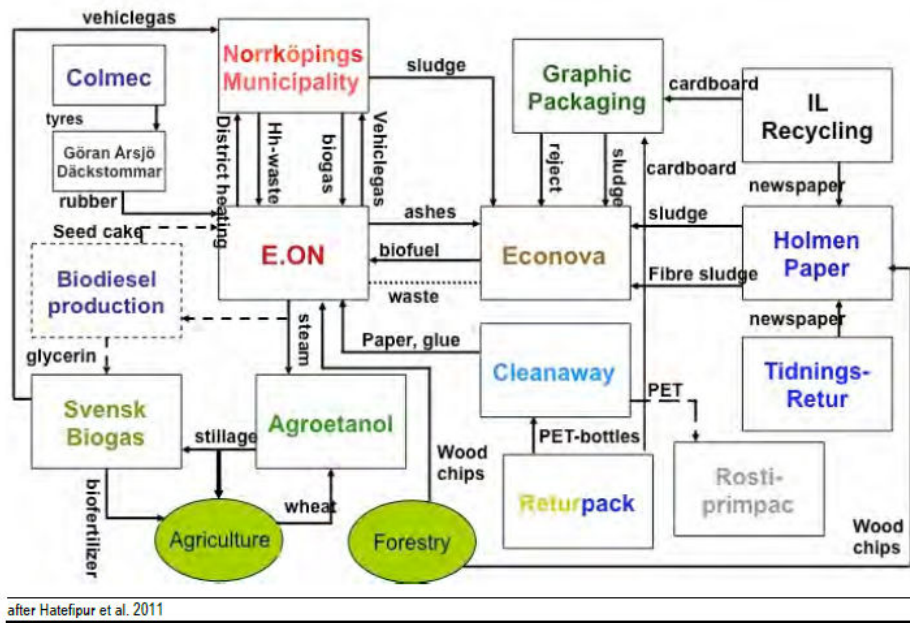
C Type III Ecosystem 1992–2003.



after Korhonen et al. 2005)

Reference: Korhonen and Snäkin (2005)

□ Norköping-Linköping, Sweden



Reference: Hatefipour et al. (2011)

□ Gladstone, Australia

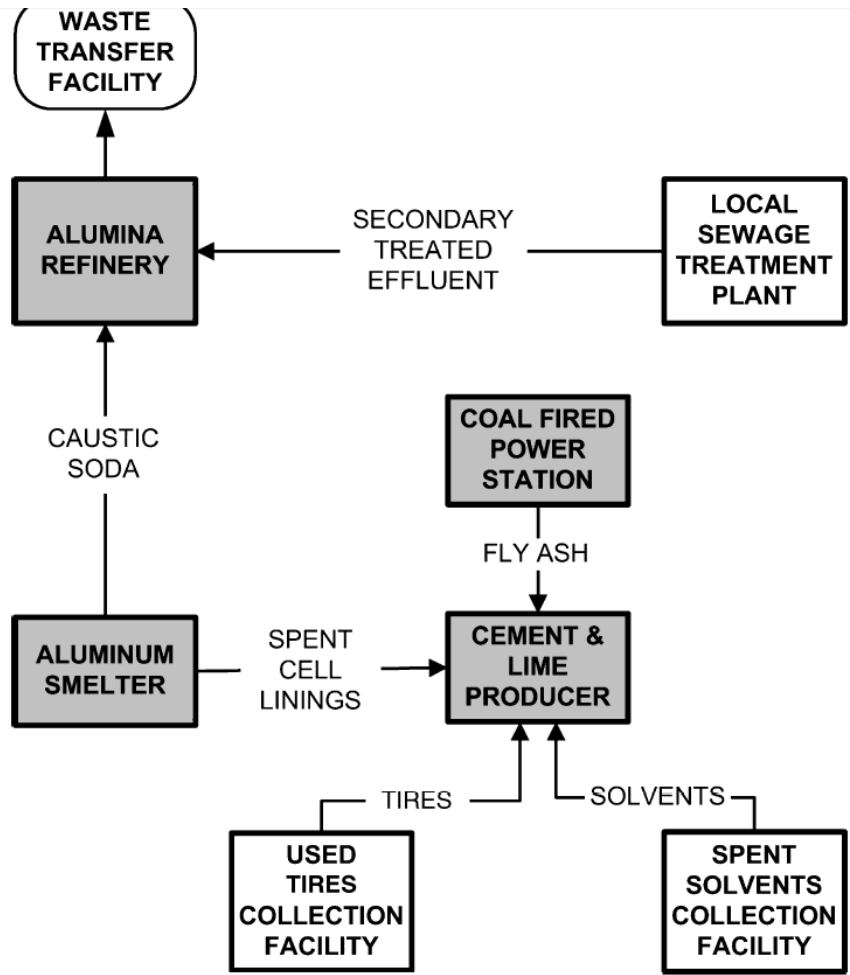
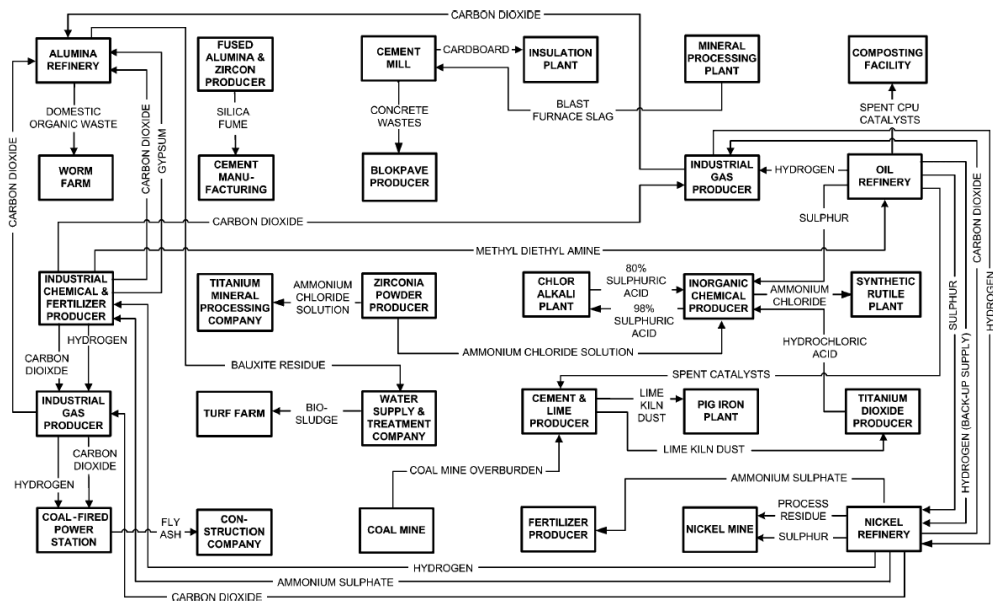


Figure 5 Existing by-product and utility synergies in Gladstone (Corder 2005). Shaded boxes indicate firms that are members of the Gladstone Area Industry Network (GAIN); unshaded boxes represent firms that are not members of GAIN.

Reference: Golev et al. (2014)

□ Kwinana, Australia

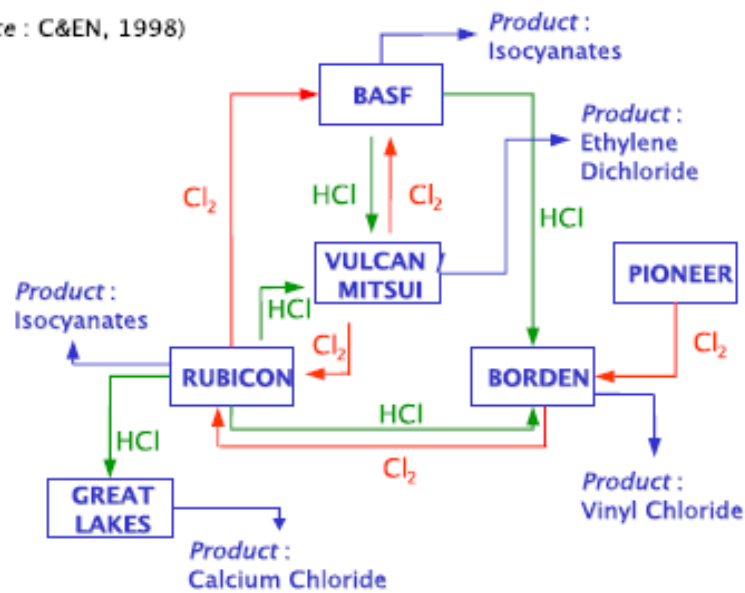


Reference: Van Beers et al. (2007)

□ Central gulf coast, USA

Fig. 52 > Gulf Coast Chlorine Exchange

(Source : C&EN, 1998)



after Francis 2003

Reference: Boons and Howard-Grenville (2009)

□ Barceloneta, PortoRico

1308

Marian R. Chertow et al.

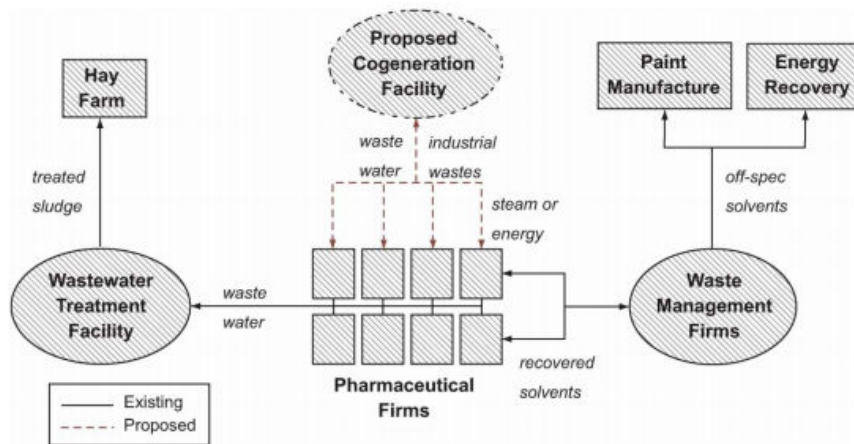


Fig. 3. Industrial symbiosis in Barceloneta, Puerto Rico

Reference: Chertow and Ashton (2009)

□ Guyama, PortoRico

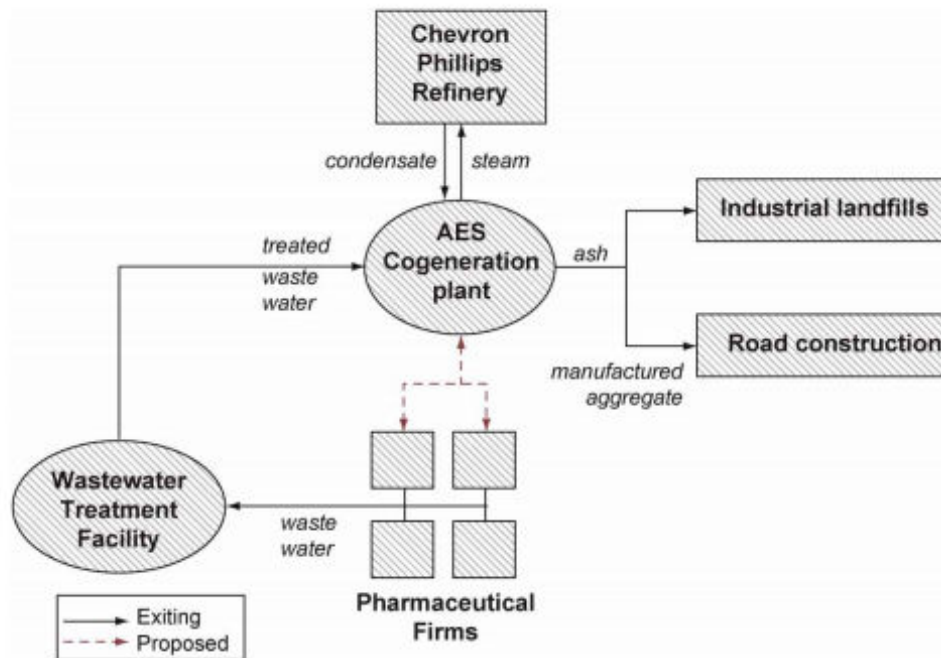


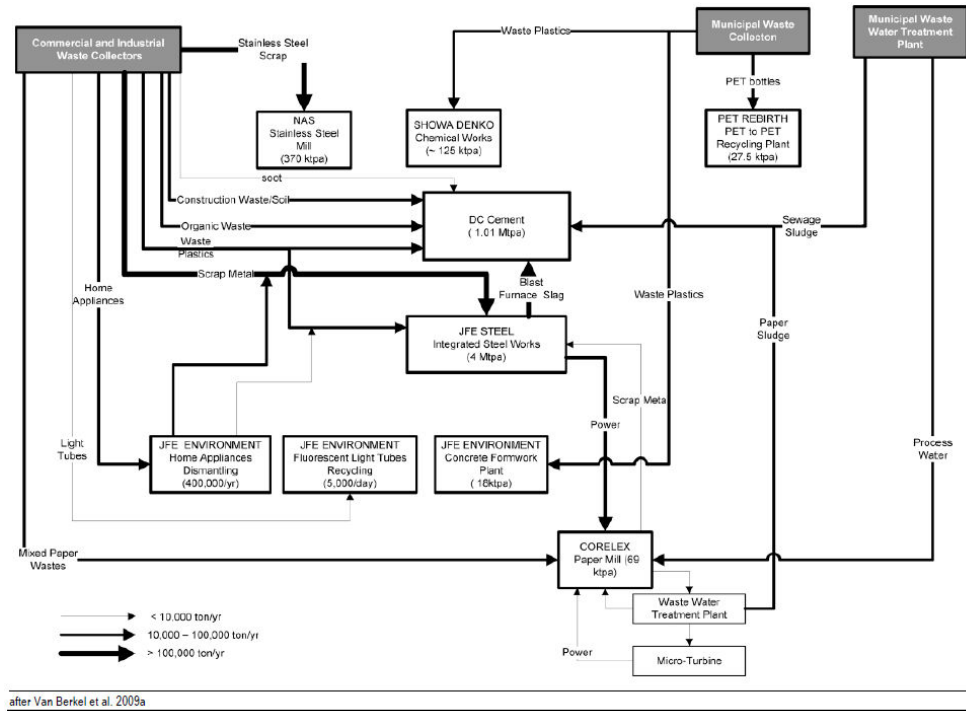
Fig. 4. Industrial symbiosis in Guayama, Puerto Rico

Reference: Chertow and Ashton (2009)

□ Kawasaki, Japan

Fig. 49 > Overview of 2009 symbioses state in Kawasaki. Note

ktpa = kiloton per annum and Mtpa = megaton per annum.



Reference: Berkel et al. (2009)

□ Shenyang Teixi, China

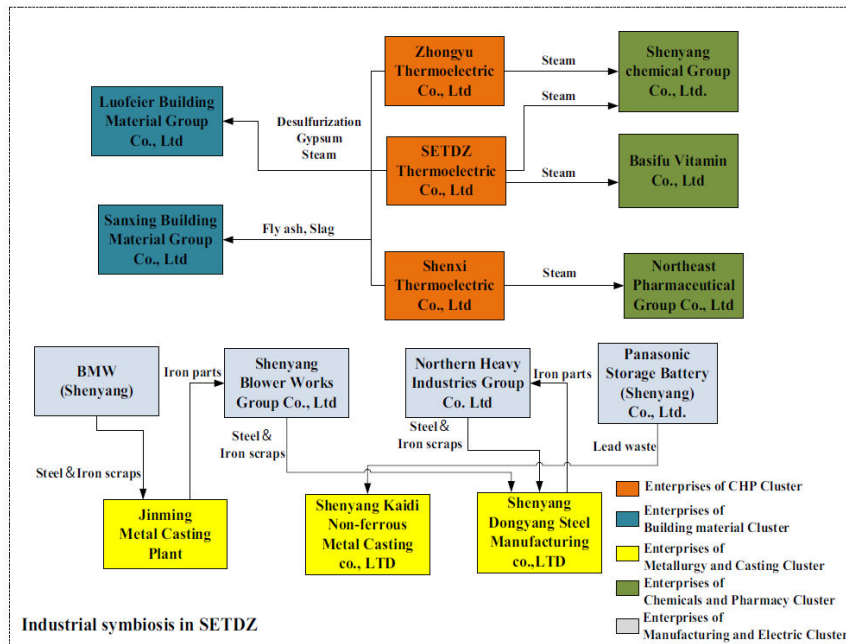
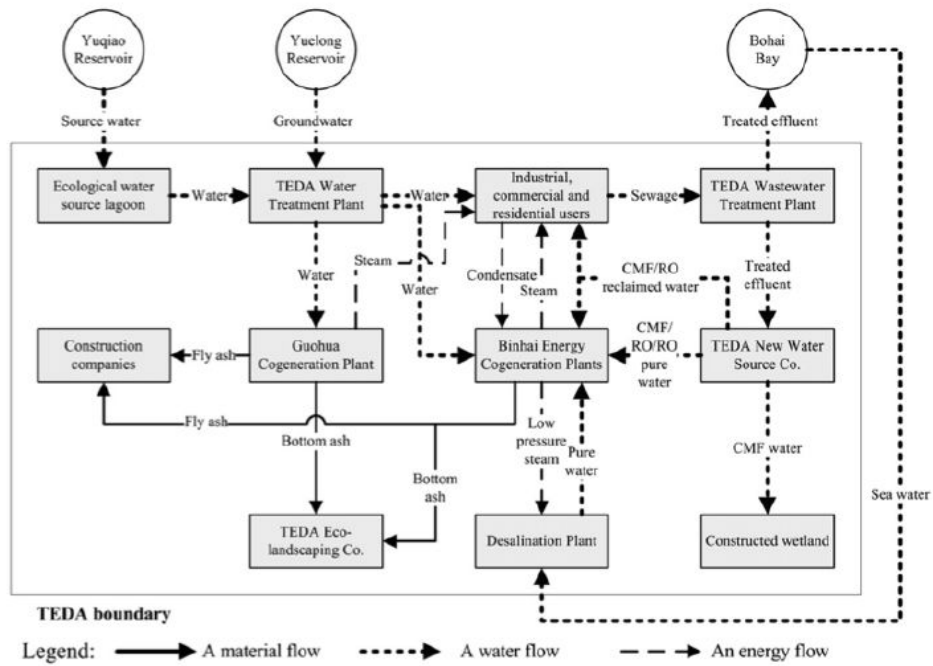


Fig. 2 Industrial symbiosis of SETDZ in 2010

Reference: Geng et al. (2014)

□ TEDA, China

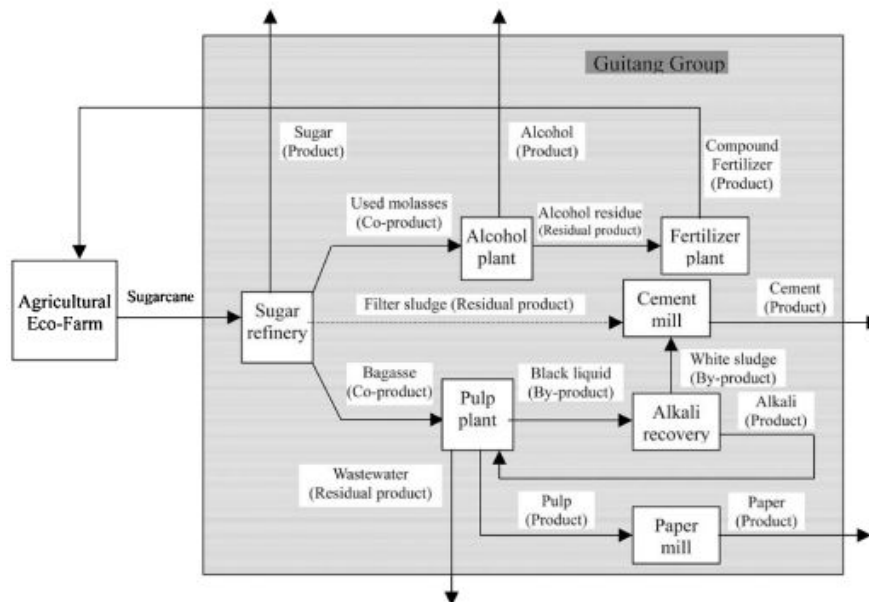
Fig. 45 > Symbiotic exchanges associated with the public utility sector



after Shi et al. 2010

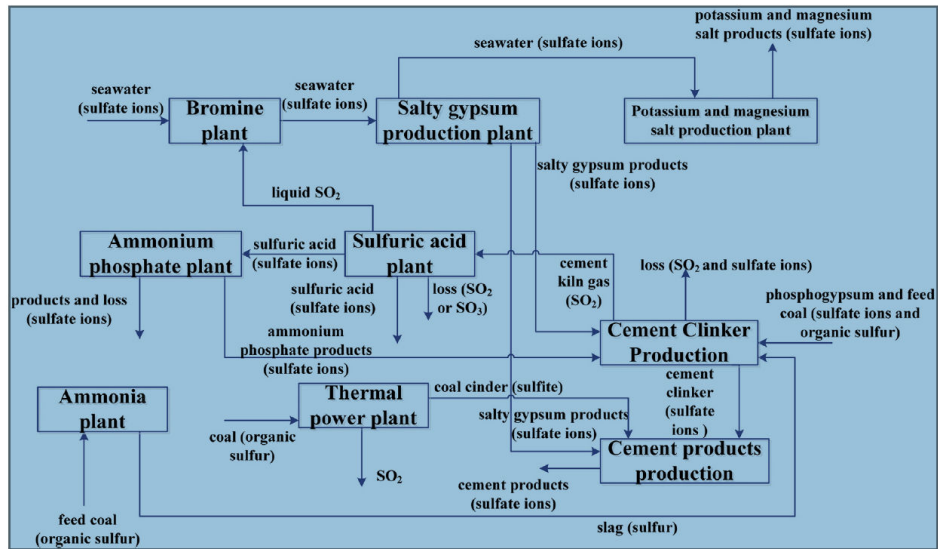
Reference: Yu et al. (2014)

□ Guitang group, China



Reference: Zhu et al. (2007)

□ Lubei, China



Reference: Zhang et al. (2015)

□ Ulsan, Korea

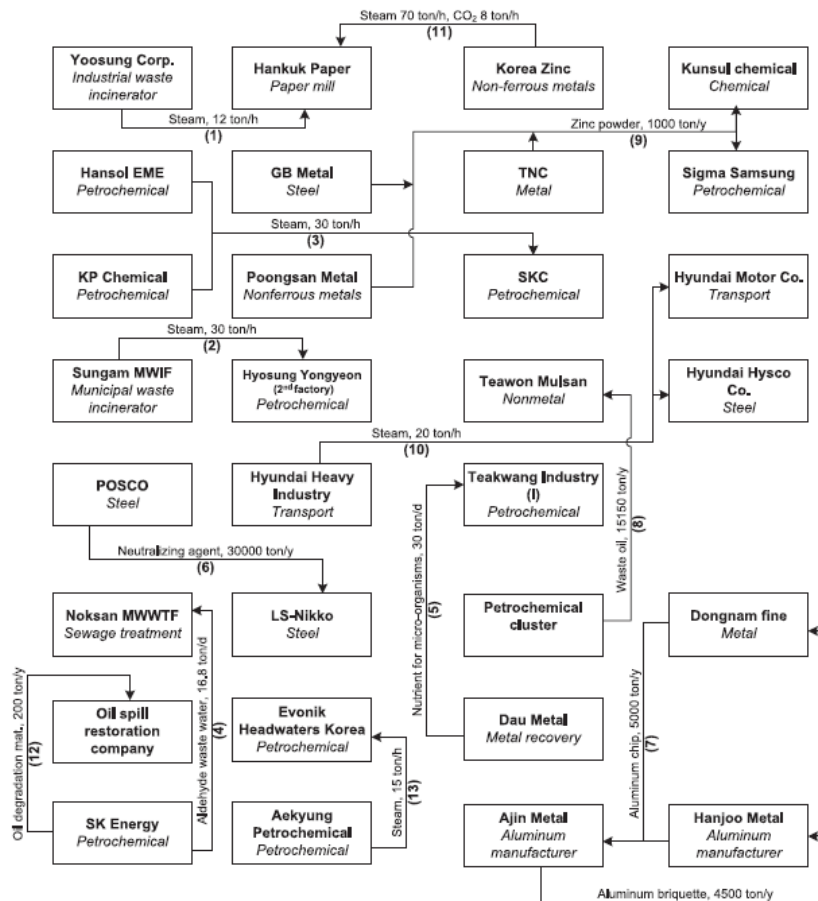


Fig. 5. Overview of symbioses developed in the Ulsan EIP (numbers within bracket along the arrows indicate the networks).

Reference: Behera et al. (2012)

Titre : Analyse économique des éco-parcs industriels : une approche par les transactions pour la valorisation des synergies et la gestion des risques

Mots clés : Economie des coûts de transaction, éco-parcs industriels, synergies industrielles.

Résumé : Les travaux présentés dans ce mémoire étudient les problématiques transactionnelles posées par le développement des éco-parcs industriels (EPI). Nos travaux visent donc à fournir une analyse économique des synergies éco industrielles (substitution de ressource, mutualisation d'infrastructures) afin de compléter les approches techniques principalement développées en sciences de l'ingénieur. Notre unité d'analyse sera donc les transactions. Nous proposons une typologie des pratiques de synergies éco-industrielles ainsi qu'une représentation de leur processus de mise en œuvre.

Nous analysons le cas de l'EPI Green Valley (France). Nous caractérisons et mettons en perspective son développement et les principaux facteurs ayant affecté son processus de déploiement. Ensuite, en faisant appel à des arguments issus de l'économie des coûts de transaction, nous proposons l'usage de contrats de long terme complexes pour organiser les transactions associées aux SI. En conséquence, un cadre de conception des contrats incluant des clauses spécifiques (tarification, pénalités, garanties) est proposé de manière à tarifier les flux et à partager le risque. Dans une dernière partie, nous étudions les décisions d'investissement en capacités mutualisées.

Title : Economic analysis of eco-industrial parks : a transactional approach for synergies valuation and risk management

Keywords : Transaction cost economics, eco-industrial parks, industrial synergies

Abstract : This thesis report aims at addressing transactional issues raised by the undertaking of eco-industrial parks (EIP) development. The economics of eco-industrial synergies (resource "flow" substitution and infrastructure/service "capacity" sharing) is investigated so as to complement existing engineering-oriented approaches. A focus is made on industrial stakeholders' interplay in industrial symbiosis (IS) and their strategic decisionmaking in terms of investment and contracting practices. First, a survey of practices actually observed in EIPs in function is conducted through a literature review. A taxonomy of eco-industrial synergies is thus proposed and an IS implementation process representation is derived.

Then we conduct a case study on the GreenValley eco-industrial park (France) Then, from economic arguments (transaction costs) we advocate the use of long term contracting in organizing IS related transactions. Following this, a contract design framework including specific provisions (tarification, penalties, warranties) is proposed in order to perform pricing of flows exchanges and risk sharing. In a last part, investment decisions in shared capacities is studied using economic modelling both in cooperative and non-cooperative game setting. Key economic parameters (size, back-up costs, scaling factor) and behavioral decisions (investment, commitment) are described and uncertainty is treated in two different approaches.