Supporting the Industrial Symbiosis practice: Emergence and Sustainability of Self-Organized Industrial Symbiosis Networks

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

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ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo:

SUPPORTING THE INDUSTRIAL SYMBIOSIS PRACTICE: EMERGENCE AND SUSTAINABILITY OF SELF-ORGANIZED INDUSTRIAL SYMBIOSIS NETWORKS

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Final Dissertation

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“We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover all the tracks, to not worry about the blind alleys or to describe how you had the wrong idea first, and so on. So there isn't any place to publish, in a dignified manner, what you actually did in order to get to do the work”.

Richard P. Feynman - Nobel Lecture: “The Development of the Space-Time View of Quantum Electrodynamics”, 11st December 1965.

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Introduction

Actually, the industrial sector plays a key role in sustaining the population needs. Traditionally, such a sector is supported by the linear model "take-make-dispose": the industrial sector uses virgin raw materials as inputs for its production processes (take) and transforms these inputs in products (make) destined to consumption. Wastes generated by production processes are disposed of in the landfill, as well as products at the end of their lifetime (dispose).

However, two recent phenomena are distressing such a model. Firstly, the world population has grown by one billion in the span of the last twelve years, reaching today 7.3 billion people, and it is growing at rate of 1.18% per year, i.e., an additional 83 million people annually. Secondly, in some developing countries the *per capita* consumptions are constantly increasing, getting closer to the level of developed countries. These phenomena have been responsible for a huge increase in the amount of natural resources extracted (required to sustain the new, higher level of consumptions) and wastes landfilled (resulting from higher production levels) to an extent which has never seen before. From one hand, since natural resources are part of the ecosystems that support the provision of several services (e.g., climate regulation, flood control, natural amenities, cultural services) the high consumption of natural resources is able to cause huge damage to these ecosystems, in terms of global climate change, landscape change, and loss of biodiversity. From the other hand, landfills are responsible for methane gas emissions (greenhouse gasses as methane are recognized the main responsible of the climate change), leachate production, and other chemical and microbiological contaminants in air, water, and soil.

The scenario so outlined shows that the world today is facing two main challenges: on the one hand, expanding the economic opportunities for a growing global population, but on the other hand, addressing the environmental pressures that, if left unaddressed, could undermine the ability to seize these opportunities. In order to tackle both these challenges contemporaneously, the industrial sector must: i) increase the amount of produced outputs; ii) reduce the amount of natural resources used as input in industrial processes and the amount of wastes landfilled. However, by adopting the "take-make-dispose" model, these goals are in contrast to each other. In fact, increasing the amount of produced outputs means further increasing the amount of natural resources extracted and wastes generated. Moreover, the amount of natural resources extracted and wastes landfilled can be reduced only if the produced output is reduced. Therefore, since the "take-make-dispose" linear model is not useful to tackle these challenges, it is no more sustainable.

Circular economy is a new economic model aimed to decouple the economic growth from the environmental degradation. Such a model is based on three principles: i) preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows, choosing technologies and processes that use renewable or better-performing resources, where possible; ii) optimizing resource yields by circulating products, components and materials in use at the highest utility at all times, i.e., designing for remanufacturing, refurbishing, and recycling to keep components and materials circulating in and contributing to the economy; and iii) fostering system effectiveness by revealing and designing out negative externalities. Circular economy is supposed to reduce the environmental impact of industrial systems and contemporaneously boost global competitiveness and generate new jobs, thus fostering sustainable economic growth. Since 2011, the European Commission stimulated the Europe's transition towards a circular economy and recognized in industrial symbiosis a useful approach to sustain such a transition.

Industrial symbiosis is an emerging field of industrial ecology concerning the collaborative management of resource flows in business networks with the aim of achieving at the same time economic, environmental, and social advantages. Resource flows mainly involve the physical exchange of materials, energy, water, and by-products among firms. Two firms create an industrial symbiosis relationship when at least one waste produced by the former is used as input by the latter. By implementing such a relationship, firms reduce the amount of both virgin natural resources used and wastes disposed of in the landfill, thus creating environmental benefits for the collectivity as a whole. Moreover, firms can gain economic benefits from the reduction of their production costs, in particular in form of lower input purchase costs and waste disposal costs. Finally, the industrial symbiosis approach may foster the creation of new jobs, then further contributing to the sustainable development of the society. When at least three different firms are involved in exchanging different resources, an industrial symbiosis network arises. Within these networks, each firm can be involved in more than one symbiotic relationship contemporaneously; moreover, relationships can arise among partners very different each other, often belonging to different production and supply chains, then forcing environmental innovations at the sectorial interface. Examples of industrial symbiosis networks are spread all over the world, both in underdeveloped economies as well as in developed countries, confirming that industrial symbiosis can be an effective strategy to pursue sustainable development. Industrial symbiosis networks can be designed by adopting a top-down approach or let emerge from the bottom, as the result of a self-organized process undertaken by the involved firms. In this regard, the literature seems to converge in considering the bottom-up approach as the most promising one.

However, self-organized industrial symbiosis networks are a tool currently underdeveloped because the industrial symbiosis approach is not fully exploited by companies. Hence, firms do not capitalize on economic opportunities, resulting in positive externalities not created for the society. Thus, the benefits currently created by the industrial symbiosis practice are lower than the benefits potentially achievable. Such an issue strongly limits the efficacy of the industrial symbiosis approach in tackling the challenges of sustainable development. Two main causes contribute to this underdevelopment: the low emergence rate of self-organized industrial symbiosis networks and the low sustainability of these networks over the long period, i.e., the capability of industrial symbiosis networks of creating benefits with continuity over time. So far, the literature focused on studying the emergence process of self-organized industrial symbiosis networks, identifying basic mechanisms as well as barriers hampering such a process. However, despite the literature provided solutions in order to overcome the barriers to the emergence process, two of these barriers remains unsolved so far: the low awareness of firms about how to integrate the industrial symbiosis approach within their business practice and the unfairly sharing of economic benefits stemming from the industrial symbiosis approach among firms. Little attention has been also dedicated to the sustainability over the long period: a theoretical framework for such an issue is completely lacking. This thesis addresses both the causes contributing to the underdevelopment of self-organized industrial symbiosis networks and is divided into two parts.

In the former, I investigated the two barriers unsolved so far. From one side, by adopting a multiple case study approach analyzing existing cases of industrial symbiosis, I formalized all the business models that firms can adopt to implement the industrial symbiosis approach and I discussed the possible business scenarios arising from the cooperation among firms, each of them adopting its own business model. Furthermore, from the other side, I designed a contractual mechanism to align the incentives among firms, fairly sharing the economic benefits stemming from the symbiotic exchanges, and tested its efficacy by adopting the agent-based simulation approach. Both these issues are particularly important to force the creation of self-organized industrial symbiosis networks, since firms are interested to cooperate in symbiotic exchanges only if they gain enough economic benefits from these exchanges.

The second part of this thesis is aimed to develop a theoretical framework for the sustainability of industrial symbiosis networks over the long period. Since industrial symbiosis networks are recognized as the analogous of the natural ecosystems in ecology and these ecosystems are characterized by high sustainability over time, I took contributions from ecology in addressing such an issue. Sustainability of natural ecosystems is affected by two features at the system level: efficiency in using natural resources and resilience to perturbations. Efficiency and resilience are two inversely related properties: in particular, efficiency can be increased only by reducing resilience and *vice versa*. However, to be sustainable over the long period, ecosystems must have enough efficiency to ensure their functions and enough resilience to resist to perturbations affecting the ability to provide their functions. The ecological literature demonstrated that sustainability of ecosystems is maximized when an optimal balance between efficiency and resilience occurs. I framed industrial symbiosis networks as industrial ecosystems providing benefits to the environment through waste exchanges. Thus, I investigated the hypothesis that sustainability of industrial symbiosis networks would be affected by efficiency in exchanging resources and resilience to perturbations. Firstly, for each of these properties, I developed a theoretical framework by analyzing them in the ecological and industrial field and I proposed numerical measures to assess efficiency and resilience. Then, I investigated the mutual relationship between efficiency and resilience and, by adopting the agent-based simulation approach, how the sustainability of industrial symbiosis networks can be maximized by properly balancing these features.

The thesis is organized as follows. Chapter 1 discusses the state-of-the-art about industrial symbiosis and industrial symbiosis networks through a critical review of the literature. Moreover, the motivation of this study, the specific research questions, and the adopted methodologies are presented. Chapter 2 addresses business models supporting the industrial symbiosis approach whereas Chapter 3 is focused on the contractual mechanisms aligning the incentives among firms. Chapter 4 and Chapter 5 are devoted to investigate the features of efficiency and resilience in the industrial symbiosis field, respectively. Chapter 6 investigates the effect of these features on the sustainability of industrial symbiosis networks. Finally, conclusions are provided.

Chapter 1. Industrial symbiosis and industrial symbiosis networks: state-of-the-art

1.1 The industrial symbiosis approach: A critical literature review

"*Industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*" (Chertow, 2000, p. 313).

In this Section, such a definition is analyzed and discussed referring to all its components.

"Industrial symbiosis engages traditionally separate entities […]"

The term "symbiosis" builds on the notion of biological symbiotic relationships in ecology. From the ancient Greek σὺν "together" and βίωσις "living", it was coined by Albert Bernhard Frank in 1877 to indicate two species that live in close association with each other. Three subcategories of natural symbiosis have been identified: mutualism, commensalism, and parasitism (Douglas, 1994). In mutualistic symbiosis, the relationship between two organisms can be considered as a form of "biological barter": one organism obtains at least one resource from the other organism in return for at least one service provided (for instance support or locomotion) (Ollerton, 2006). Both the organisms benefit from such a symbiotic relationship because of their performance improvements. This situation does not occur in parasitism and commensalism, where only one organism benefits from the symbiotic relationship. This organism obtains nutrients or exploits services provided by the other organism, without providing anything in return. The difference between the two subcategories is that, while in commensalism one organism benefits from symbiosis without affecting the performance of the other, in parasitism one organism benefits at the expense of the other, i.e., the performance of the other organism is reduced (Table 1.1).

Table 1.1 Impact on two organisms in each symbiosis subcategory.

	Organism A	Organism B
Mutualism	Positive	Positive
Commensalism	Positive	None
Parasitism	Positive	Negative

The industrial symbiosis (IS) among "traditional separate entities" evokes the metaphor of natural symbiosis among different organisms in ecosystems (Ayres, 1989; Korhonen, 2001). In fact, entities involved in relationships of IS correspond to organisms among which a symbiotic relationship occurs. In this case, the involved entities can be different production processes, facilities, companies, production and supply chains (Baas, 1998; Chertow, 2000; Lombardi and Laybourn, 2012).

in "[…] physical exchange of materials, energy, water, and by-products […]"

Two separate entities, A and B, implement a symbiotic relationship when at least one waste produced by the former is used as input (material or energy) by the latter (Lombardi and Laybourn, 2012). Similarly to symbiotic relationships in the natural field, the entity B obtains resources for itself in return for a service provided (B is disposing of wastes in the advantage of A).

Relationships of IS are actually implemented by entities belonging to several industrial sectors, for instance chemical (Dong et al., 2013), iron and steel (Johansson and Söderström, 2011), energy (Pearce, 2008; Martin and Eklund, 2011; Gonela and Zhang, 2014), forest (Pakarinen et al., 2010; Sokka et al., 2011b; Wolf and Petersson, 2007), mineral (Van Beers et al., 2007) construction (Ammenberg et al., 2015; Hashimoto et al., 2010), agrifood (Ometto et al., 2007; Yang and Feng, 2008; Zhu et al., 2007). These relationships may occur among entities belonging to the same industrial sector or, conversely, to different sectors. In the latter case, the IS approach pushes companies to search and discover solutions at the inter-sectorial interface, revealing to be a great opportunity to enhance eco-innovations (Mirata and Emtairah, 2005).

Although the IS practice is typical of industrial contexts, some studies have investigated its extension to urban areas, in order to use wastes generated into these areas for industrial applications. Two different approaches are under investigation. The former concerns the exploitation of previously discarded wastes from households and commercial activities. Japan's Eco-Town Program spearheaded in Japan the implementation of such an approach, aimed to enhance the economic and environmental benefit from the close geographic proximity of industrial and urban areas. Approximately 1.65 billion USD were invested in 61 innovative recycling projects involving 26 Japanese towns, with an average government subsidy of 36% (Geng et al., 2010a; Hashimoto et al., 2010; Ohnishi et al., 2016, 2012; Van Berkel et al., 2009). Subsequently, some Chinese cities implemented similar projects (Dong et al., 2013, 2014; Li et al., 2015; Liu et al., 2011). The latter approach concerns the adoption of the IS approach in port areas to support regional eco-industrial development (Mat et al., 2016). In particular, wastes generated within ports can be exploited into the same area or for external industrial applications. In this regard, Cerceau et al. (2014) carried out a cross-case analysis of symbiotic initiatives concerning wastes generated in 23 port areas spread over the world, identifying nine different patterns based on temporal and spatial characteristics of these initiatives.

The implementation of the IS approach has been also proposed for the agricultural field, concerning the exploitation of organic wastes to produce biofuels and fertilizer. Alfaro and Miller (2014) discussed the adoption of the IS approach on smallholder farms scale by using optimization techniques to maximize farm output while minimizing wastes. Moreover, Yazan et al. (2015) and Yazan et al. (2016a) investigated the production chain of second-generation biofuels from pig manure in the Netherlands, with the aim to identify the main technical and economic factors able to affect the implementation of such a chain. Applications in the following chapters will analyze cases concerning all these fields (industrial, urban, agricultural).

pursuing "[…] a collective approach to competitive advantage […]"

By exchanging resources, each firm gains economic benefits in form of lower production costs. In particular, firms producing wastes reduce disposal costs whereas firms using wastes as inputs reduce purchase costs. These economic benefits can be source of competitive advantage for firms involved in symbiotic exchanges (Esty and Porter, 1998; Yuan and Shi, 2009). Hence, referring to the comparison with natural symbiosis, IS can be conceptualized as a form of mutualistic symbiosis because all the involved firms improve their economic performance. Such an awareness pushes firms to implement the IS approach: in fact, firms are willing to be involved in IS relationships because of the economic benefits that they can obtain (Lyons, 2007). Moreover, cases of IS in urban areas demonstrated that also citizens can gain economic benefits in form of lower taxes on municipal wastes collection and disposal.

Moreover, the IS approach is able to generate environmental benefits, in the advantage of the collectivity as a whole. In this regard, three main benefits can be recognized. The most evident one is the reduction in the amount of wastes disposed of in the landfill. Actually, landfills are responsible for chemical and microbiological contaminants in air, water, and soil, as methane gas emission and leachate production (e.g., Chofqi et al., 2004; Fatta et al., 1999; Kjeldsen et al., 2002). Hence, reducing the amount of wastes so disposed means to limit the negative environmental impact of landfills. Moreover, the use of wastes as inputs allows to reduce the amount of virgin inputs and energy used in production processes. This benefit is particularly significant because the last ten years have been characterized by a huge increase in the amount of natural resources extracted, to an extent which has never seen before (Krausmann et al., 2009; Wiedmann et al., 2015). Natural resources are essential inputs for production processes and the extraction, treatment, and disposal of such resources are an important source of income and jobs in many countries. However, natural resources are also part of the ecosystems that support the provision of services such as climate regulation, flood control, natural amenities, and cultural services. In this regard, the high consumption of natural resources can cause huge damage to the ecosystem, such as global climate change, landscape change, and loss of biodiversity (e.g., Donohoe, 2003; Weber et al., 2008). In turn, reduction in the energy consumptions is a high-important benefit. In fact, since a huge amount of the electric energy (about 60% of total generation) is actually produced by exploiting fossil fuels (IEA, 2014), the electricity consumption is one of the main reasons of greenhouse gas (GHG) emissions (Soytas et al., 2007), which are widely recognized as the principal responsible for the climate change (IPCC, 2014). Finally, the IS approach allows to reduce the CO_2 emissions because of: i) lower amount of virgin inputs extracted; ii) lower transportation of virgin inputs from input production facilities to input use facilities; iii) lower transportation of wastes from waste production facilities to landfills; iv) lower emissions from waste-to-energy processes compared with traditional energy production processes. This result was discovered by comparing GHG emissions generated as a whole by a given industrial area for two different scenarios: when IS occurs and when IS does not occur (e.g., Chertow and Lombardi, 2005; Jensen et al., 2011; Sokka et al., 2011a; Zhang et al., 2013). Several studies in the literature were aimed to quantify the economic and environmental benefits generated by the implementation of the IS approach within a given industrial or urban area. Table 1.2 highlights environmental and economic benefits assessed by some of these studies.

Table 1.2 Environmental and economic benefits of IS quantified by some selected studies.

Case	Environmental benefits	Economic benefits	Reference
Ulsan (South Korea)	227.36 kt/year CO_2 avoided	68.52 million dollars/year Average payback period of symbiotic investments lower than one year	(Behera et al., 2012)
Jinan City (China)	3944.05 kt/year CO_2 avoided		(Dong et al., 2014)
Liuzhou (China)	2347.88 kt/year CO_2 avoided		(Dong et al., 2014)
Kawasaki (Japan)	565 kt/year wastes not landfilled 41.3 kt/year CO_2 avoided	130 million dollars/year	(Hashimoto et al., 2010; Van Berkel et al., 2009)
Mysore (India)	897.21 kt/year wastes not landfilled		(Bain et al., 2010)
Guitang Group (China)	~650 kt/year wastes not landfilled	+5521% of profits for the industrial group	(Yang and Feng, 2008)
Kymenlaakso (Finland)	240 kt/year CO_2 avoided		(Sokka et al., 2011b)
Kalundborg (Denmark)	217.8 kt/year wastes not landfilled 49 kt/year fossil fuels saved 1.2 Mt/year water saved 130 kt/year CO_2 avoided		(Christensen, 2006)
Tianjin Economic-Technological Development Area (China)	~650 kt/year wastes not landfilled ~2.7 Mt/year water saved		(Shi et al., 2010)
Campbell Industrial Park (Hawaii)	~150 Ml/year water saved 17.8 kt/year coal saved		(Chertow and Miyata, 2011)
ISIP Industrial Park (China)	From 56 to 223 Kg CO_2/t steel produced		(Zhang et al., 2013)
Guayama (Puerto Rico)		~300000 $/year of avoided costs	(Chertow and Lombardi, 2005)

Finally, from the social point of view, the adoption of the IS approach is able to create new firms and new jobs.

The usefulness of the IS approach has been also recognized by European Commission, which has explicitly recommended the adoption of such an approach to boost production efficiency (European Commission, 2015, 2011). Specifically, the Roadmap to a Resource Efficient Europe sustains that the IS approach could reduce the amount of material directly used in the EU economy and increase firms competitiveness, saving 1.4 billion of euros per year and generating 1.6 billion of euros in sales.

… whose keys are "collaboration and the synergistic possibilities offered by geographic proximity"

Since IS naturally involves two or more different entities, their mutual collaboration is considered fundamental for the development of the IS practice (Ashton, 2008; Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011a, 2009; Ehrenfeld and Gertler, 1997; Gibbs, 2003; Hewes and Lyons, 2008; Jacobsen and Anderberg, 2005; Sterr and Ott, 2004). In particular, collaboration among firms involved in symbiotic exchanges requires the cooperative management of physical and economic flows, sharing confidential information with partners, and solving technical, economic, and organizational problems related to the symbiotic interaction (Hewes and Lyons, 2008; Mirata, 2004). Collaboration plays an important role for IS because, without it, companies are unwilling to link processes in a manner that may affect the ways in which they choose to operate (Gibbs, 2003; Lambert and Boons, 2002). Moreover, such a collaboration can be enhanced by the existence of personal relationships among managers of the involved companies. This conviction is based on several publications that emphasize the role of personal relationships in generating trust among companies and discouraging malfeasance during the interaction among them (e.g., Granovetter, 1985) and it is supported by empirical experiences of IS. Trust can also be a key influence on the development of symbiotic relationships as it helps to embed and maintain the level of relationships required to develop and distribute knowledge and technology (Murphy, 2006). Moreover, trust plays an important role in reducing transaction costs among companies (Bönte, 2008). In fact, without trust and cooperation, the level of knowledge exchange required to facilitate IS can be difficult and costly to obtain (Christensen, 1994). Trust is built over time, through the repeated interactions of actors that result in positive outcomes (Granovetter, 1985). These interactions are likely to be enhanced by geographical proximity, which promotes opportunities for face-to-face contacts, facilitating exchanges of knowledge and know-how among companies. Therefore, it is widely recognized that trust among companies could be enhanced by their geographic proximity (Hewes and Lyons, 2008). In addition to the positive role in developing trust, geographical proximity may further reduce the costs of transaction among different companies (Williamson, 1996) and make easier the information sharing. Nevertheless, cases of IS among firms at the regional level have been observed to arise in numerous locations. In these cases, the average distance traveled for symbiotic exchange ranges between 20 Km and 30 Km (Bain et al., 2010; Jensen et al., 2011; Shi et al., 2010; Van Beers et al., 2007). In this regard, it has been observed that symbiotic exchanges in a regional scale have to challenge several disadvantages. In particular, companies have to sustain higher costs of overcoming distances and to implement solutions logistically more complex. Moreover, it could be difficult to establish enough levels of trust and coordination among companies. Finally, communication among companies could be more complex, as well as it could prove problematic to collect and homogenize the resource data required to enable the identification of prospective partners (Sterr and Ott, 2004). However, the regional scale allows to include greater number and variety of actors, able to increase the amount and typology of exchanged wastes, as well as the available solutions to use wastes in place of inputs, favoring higher number of symbiotic relationships (for a more detailed discussion of such an issue, see Section 1.2) (Korhonen, 2001a). In turn, the effect of scale economies can be better exploited (Sterr and Ott, 2004). In this regard, Lyons (2007) investigates what is the best geographic scale for symbiotic exchanges to take place. His results suggest that there is no preferable scale at which loop closing should be organized: instead, such a scale is dominated by the spatial economic logic of the transactions of the firm involved.

Actually, is widely recognized that "*Geographic proximity—or locational factors more broadly—do not cause the formation of an exchange network, but, importantly, enable it. […] Geographic proximity, then, becomes an enabler—along with other characteristics such as industry mix, availability and value of resources, information, and regulatory structures—of* *what ultimately drives industrial symbiosis: the ease with which relationships and institutions form*" (Chertow and Ehrenfeld, 2012, p.22).

1.2 Industrial symbiosis networks: Theory and Models

The IS approach exploits business networks to promote industrial activity ecologically sustainable (Chertow et al., 2004). Business networks are composed of at least three different entities involved in mutual collaboration (Polenske, 2004). These networks are considered different from one-to-one of business alliances because: i) coordination tasks are more complex; ii) each business entity can be involved in more than one cooperative relationship contemporaneously; and iii) relationships can arise among partners very different each other (Hage and Alter, 1997)

An industrial symbiosis network (ISN) is a business network made by all the firms belonging to a given geographic area among which IS relationships exist (Fichtner et al., 2005). Moreover, ISNs are an example of industrial ecosystems, which are considered as the analogous of ecosystems in ecology (Côté and Hall, 1995; Graedel, 1994; Liwarska-Bizukojc et al., 2009). An ecosystem is a natural system consisting of all plants, animals, and micro-organisms (biotic factors) in a given area interacting among them and with the external environment (Christopherson, 1997). The interaction among organisms makes the ecosystem able to support a given set of functions, through which it is able to create services for the external environment as well as for the organisms belonging to the ecosystem (Folke et al., 2004; Walker et al., 2006). Similarly,

> "*An industrial ecosystem is a community or network of companies and other organizations in a region who choose to interact by exchanging and making use of by-products and/or energy in a way that provides one or more of the following benefits over traditional, non-linked operations: i) Reduction in the use of virgin materials as resource inputs; ii) Increased energy efficiency leading to reduced systemic energy use; iii) Reduction in the volume of waste products requiring disposal (with the added benefit of preventing disposal-related pollution) ; iv) Increase in the amount and types of process outputs that have market value*" (Lowe, 1997, p. 57).

Similarly to ecosystems in ecology, firms belonging to ISNs, which correspond to organisms involved in natural symbiotic relationships (see Section 1.1), perform given functions by interacting each other. These functions correspond to the waste exchanges among firms (Korhonen, 2001a; Korhonen and Baumgartner, 2009), where firms can perform the role of producing the waste and/or using the waste as inputs. By means of firms' interaction in waste exchanges, the ISN is able to generate two main services: i) creating economic benefits for firms (organisms); and ii) creating environmental benefits for the collectivity as a whole (external environment). Hence, ISNs can be characterized by two kinds of performance: economic and environmental. The higher the created benefits, the greater the performance of ISNs. Whilst the literature converged in using the economic benefits created by the IS relationships to evaluate the economic performance of ISNs, different approaches have been proposed to assess the environmental performance of ISNs. The most simple approach is the assessment of the amount of wastes not disposed of in the landfill as well as the amount of virgin inputs not purchased from outside the ISN (Behera et al., 2012; Sun et al., 2016; Van Berkel et al., 2009; Yazan et al., 2016b). However, such an approach has two important limitations: i) the indicators are defined at the level of specific symbiotic flows and they cannot be extended to the ISN as a whole; and ii) GHG emissions are not taken into account. Indicators at the ISN level was subsequently adopted from MFA (e.g., Geng et al., 2009; Sendra et al., 2007) and LCA (Life cycle assessment) (e.g., Liu et al., 2011; Singh et al., 2007) approaches, as well as indicators of carbon footprint and environmental footprint (Albino and Fraccascia, 2014; Ohnishi et al., 2017) have been used. Moreover, further indicators have been adopted in order to take into account economic and environmental benefits at the same time, in particular eco-efficiency indicators (e.g., Park and Behera, 2014; Salmi, 2007) and emergy analysis indicators (e.g., Fan et al., 2017; Geng et al., 2010b; Liu et al., 2016a, 2016b)

Given the important economic and environmental role of IS, the study of the mechanisms leading to the formation and development of ISNs has been an important topic of analysis. There are two schools of thought regarding this. The former argues that ISNs should be "designed" by adopting a top-down approach, such as the planned eco-industrial park model (Behera et al., 2012; Boons and Baas, 1997; Park et al., 2008; Shi et al., 2010; Van Berkel et al., 2009; Zhang et al., 2010). An eco-industrial park is made by different firms located within the same geographic area, in close proximity each other, which collaborate in IS relationships as well as in sharing utilities and infrastructures. Table 1.3 shows some definitions of eco-industrial parks provided by the literature.

Table 1.3. Selected definitions of eco-industrial park.

Definition	Reference
A large tract of land, sub-divided and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms	(Peddle, 1993)
An eco-industrial park is an industrial system which conserves natural and economic resources; reduces production, material, energy, insurance and treatments costs and liabilities; improves operating efficiency, quality, worker health and public image; and provides opportunities for income generation from use and sale of wasted materials.	(Côté and Hall, 1995)
An eco-industrial park is a community of manufacturing and service businesses seeking enhanced environ- mental and economic performance through collaboration in managing environmental and resources issues including energy, water and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would have realized if it optimized its individual interests.	(Lowe et al., 1995)
A community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic and environmental quality gains, and equitable enhancement of human resources for the business and local community.	(U.S. President's Council on Sustainable Development, 1996)
An industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological and social relationships	(U.S. President's Council on Sustainable Development, 1996)

"*This model includes a conscious effort to identify companies from different industries and locate them together so that they can share resources across and among them. Typical U.S. planning for these systems has involved the formation of a stakeholder* *group of diverse actors to guide the process and the participation of at least one governmental or quasi-governmental agency with some powers to encourage development, such as land use planning and/or zoning, grant giving, or long-term financing*" (Chertow, 2007, p. 21). Eco-industrial parks are created by adopting the "anchor tenant option". Accordingly, at least one anchor tenant is identified, i.e., a major firm requiring high amount of inputs and/or producing high amount of wastes (such as pulp and paper mill, food-processing facility, or electricity generating station), to serve as attractor by its prestige and potential for other firms to be waste suppliers or customers. Thus, these other firms are located in their close proximity (Ayres, 1994; Lowe, 1997).

The latter school affirms that ISNs should be allowed to emerge from the bottom, as the result of a spontaneous, self-organized process undertaken by the firms involved (Chertow and Ehrenfeld, 2012; Gibbs and Deutz, 2007; Heeres et al., 2004). Such a model has been defined as "self-organized model": "*In this model, an industrial ecosystem emerges from decisions by private actors motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion. The individual initiative to begin resource exchange faces a market test and if the exchanges are successful, more may follow if there is on-going mutual self-interest. In the early stages there is no consciousness by participants of "industrial symbiosis" or inclusion in an "industrial ecosystem," but this can develop over time. The projects can be strengthened by post facto coordination and encouragement*" (Chertow, 2007, p. 21). Empirical cases demonstrate that both these models can be successful (e.g., Mirata, 2004; Jacobsen, 2006). Table 1.4 shows some empirical cases of both planned and self-organized ISNs, as well as some network features.

Table 1.4. Some empirical cases of ISNs.

Name of symbiosis industrial network	Typical facilities involved	Materials involved	Number of firms	Connectivity	References
Kalundborg (Denmark)	Coal-fired power plant, pharmaceuticals, gypsum board, oil refining, fish farming	Water, wastewater, sulfur, steam, sludge, fly ash, yeast and organic residuals	10~20	Core-periphery	(Ehrenfeld and Gertler, 1997; Jacobsen, 2006)
Guayama (Puerto Rico)	Coal-fired power plant, chemical refining, pharmaceuticals	Wastewater, condensate, steam, ash	10~20	Hub-and-spoke	(Chertow and Lombardi, 2005)
Guitang Group (China)	Sugar refining, alcohol, pulp and paper milling, cement, alkali recovery, agriculture	Sludge, alcohol, fertilizer, alkali	10~20	Core-periphery	(Yang and Feng, 2008; Zhu et al., 2007)
Ulsan (South Korea)	Oil, chemicals, incineration, metal processing, paper milling	Wastewater, biogas, steam, metal	>500	Hub-and-spoke	(Behera et al., 2012)

Table 1.4. Some empirical cases of ISNs (continued from previous page).

Name of symbiosis industrial network	Typical facilities involved	Materials involved	Number of firms	Connectivity	References
Kwinana (Australia)	Coal-fired power plant, chemicals, fertilizer producers, cement, construction, oil refining	Organic waste, sludge, acid, ash, dust, chemical catalysts, organic waste, energy production	30~50	Hub-and-spoke	(Van Beers et al., 2007)
Styria (Austria)	Sawmills, mining, textiles, chemicals, power plant, board industry, plastic production, ceramic industry, cement plant, material dealers, iron manufacturing, agriculture, associations	Ash, plastics, sludge, iron scrap, wood and paper, heat, petrol coke, slag, dust, oil	50~100	Core-core	(Posch, 2004)
Tianjin Economic Development Area (China)	Pharmaceuticals, food and beverages, electronics, machinery, others	Water, metals, chemical substances, ash, slag, organic residues	>500	Periphery-periphery	(Shi et al., 2010)
Rotterdam Harbor (The Netherlands)	Chemicals, cement, oil refining, incinerator	Heat, energy	80~100	Periphery-periphery	(Baas, 2008)

However, in recent years scholars seem to have converged in considering the self-organized approach as the most promising one, because it has been proven to be more resilient to perturbations, such as changes in production levels, in symbiotic flows, in the dimension and the number of the actors involved (Chertow, 2009). In this regard, three models explaining the creation and the development of self-organized ISNs have been proposed by the literature (Table 1.5, Table 1.6, and Table 1.7).

Table 1.5. Model for the development of self-organized ISNs proposed by Baas and Boons (2004).

Baas and Boons (2004): 3-stages model: Regional efficiency, Regional learning, Sustainable industrial district
Regional efficiency. "*Autonomous decision-making by firms; co-ordination with local firms to decrease inefficiencies (i.e. "utility sharing"). Such activities may be facilitated by local government authorities, existing co-operative arrangements between entrepreneurs, in short: local social networks. This phase is characterized by identifying and make use of existing win-win situations*".   **Regional learning**. "*Based on mutual recognition and trust, firms and other partners exchange knowledge, and broaden the definition of sustainability on which they act. In this phase, other stakeholders (local citizens, grass roots movements) may become involved as well. Thus, both goal and range of membership broaden*".

Table 1.5. Model for the development of self-organized ISNs proposed by Baas and Boons (2004) (continued from previous page).

Sustainable industrial district. "*Actors develop an—evolving—strategic vision on sustainability and base their activities on this vision*".

Table 1.6. Model for the development of self-organized ISNs proposed by Doménech and Davies (2011b).

Doménech and Davies (2011b): 3-stage model: Emergence, Probation, Development and expansion
Emergence. "*A first phase in the development of IS networks is the emergence of the network. Some main conditions seem to characterize the contexts where IS emerge (Domenech and Davies, 2009). The conditions are the following. (I) Stringent and rapidly evolving regulatory frameworks. (II) Waste-flow exchanges require customized, non-standard, applications or involve an innovative component or approach, and, therefore, imply uncertainties with regards to the outcomes and process. (III) As a result of the need for customized solutions, high coordination is required, which implies frequent interaction between companies, favouring the transfer of tacit knowledge, 'learning by doing' and the creation of a shared culture or 'macroculture' (Jones et al., 1997).* *In this first phase, initial ties are developed and some straightforward cooperation opportunities explored. Generally, these first ties do not require complex transformation processes, technological upgrades or innovation, but they set the basis of the dynamics of cooperation. The formation of the network may be the result of a spontaneous process, like the network in Kalundborg and Sagunto, or be initiated by a policy actor, as in the case of NISP*". **Probation**. "*The next phase in the development of IS networks is the probation phase […]. At this stage, network members have a general knowledge of the dynamics of the network and the opportunities of potential exchanges and cooperation. First experiences of exchanges have generated and feedback from them permeates the network, through more or less informal channels that might vary from comments from members in informal meetings to more formalized accounts of the experiences such as publication of case studies. This phase is crucial, as failure in the realization of the opportunities may lead to the early collapse of the initiative. The probation phase constitutes a first step in the development of embeddedness for a selected group of actors among which exchange ties have taken place. The experience of the cooperation generates trust and 'learning by doing', decreasing the risk associated with further exchanges*". **Development and expansion**. "*Building on the experiences of the probation period, the network enters a phase of development and expansion […] by the building of new linkages and/or the deepening of the existing relationships. Continuous interaction and accumulation of experiences of cooperation allow the thriving of embedded ties, governed by trust, tacit knowledge and joint problem-solving, and generate routines of cooperation that significantly reduce the transaction costs associated with it. More experiences of interaction increases the possibilities of further potential exchanges (a) by widening the material and knowledge basis of the system and (b) through the mechanisms of referral and transitivity (assuming that the referred parties will behave cooperatively), which favour the identification of other potential linkages and actors, deepening the level of embeddedness of the network as a whole*".

Table 1.7. Model for the development of self-organized ISNs proposed by Chertow and Ehrenfeld (2012).

Chertow and Ehrenfeld (2012): 3-stages model: Sprouting, Uncovering, Embeddedness
Sprouting. "*During this stage, a few linkages form, but the system is relatively disordered with respect to the flows of materials and energy back into trade rather than into waste disposal sinks in the broader environment. There is nothing particular about these early events that may be visible to an observer, rather, they are indistinct relative to the background at this point. These linkages occur for many reasons, including economic efficiency (Baas and Boons 2004), response to regulatory pressure, social relationships, resource security, rising cost of waste disposal, and so forth. In most cases these linkages come and go just as traditional trade linkages rise and fall along*

Table 1.7. Model for the development of self-organized ISNs proposed by Chertow and Ehrenfeld (2012) (continued from previous page).

the supply chains of firms, even if they are ones that produce public goods benefits to the environment, since that happens without notice or intent".   **Uncovering**. "*Stage 2 would not exist unless some of the structures forming and unforming in Stage 1 arose sufficiently so as to be distinct to develop in a more orderly fashion. Such emergent behavior eventually becomes visible to an observer gazing down at the system. I have also seen that many business clusters exchanging materials and energy for mutual economic benefit can produce positive environmental externalities relative to the social costs of practices that involve discarding waste directly into the environment, thus causing the negative effects of waste disposal and pollution. Two firms can accomplish this together through linked resource exchanges that reduce such negative externalities. To the extent that additional firms join the network and further reduce preexisting negative externalities, the public benefits will be greater. At some point the system begins to produce the positive environmental externalities discussed, which serve two functions. They enable the system to remain in stasis by preventing the deterioration of the milieu and the factors of production. When these externalities become known to the actors, they carry a value that can be used to provide stability and even growth. […] The further growth of the network "caused" by such institutional processes is, then, some form of intentional industrial symbiosis*".   **Embeddedness**. "*Embeddedness occurs over time. On the positive side, it can continually reduce transaction costs and uncover new benefits not considered in earlier economic calculations, although the possibility also exists that relations could become insular and thus inhibit innovative activity (Granovetter 1985)*".

Despite conceptualized by different authors, these models show several common issues. Each model identifies three different stages for the development of ISNs (compared in Table 1.8). In the first stage, single symbiotic relationships are created, independently from each other, as the result of a top-down or bottom-up approach, indifferently. Two main drivers push the creation of self-organized IS relationships: i) exploiting the opportunity to achieve economic benefits (proactive approach); ii) responding to regulatory or economic pressure (for instance, firms are forced by the government to reduce the environmental impact or the increasing competition forces them to reduce their production costs) (reactive approach) (Ashton, 2011; Lyons, 2007). In the subsequent two phases, firms acquire the awareness to being part of a network of firms, among which symbiotic relationships take place. Economic and environmental benefits created by these relationships become visible even from outside the ISN. By continuous interactions among firms, trust is developed and transaction costs are reduced. As a consequence, the potential to develop additional relationships among the existing firms is created. Moreover, the ISN tends to expand because new firms enter into the network, contributing to further increase the amount of created benefits. Zhu and Ruth (2014) stated that a self-organized ISN grows in a preferential process, with each firm's probability to develop a new IS relationship proportional to the number of its existing symbiotic relations. Moreover, such a preferential growth may be converted to more homogeneous development when institutional arrangements are present, such as firm-organized coordinative agencies, government-supported facilitating agencies, or government planning and policy enforcement. In fact, they can help disadvantaged firms to improve their capabilities to join or build IS, diminishing the disparities among firms. However, in all cases, the key to the development of the ISN is that each of the participating parties obtains an economic benefit enough to discourage it to leave the ISN (e.g., Ehrenfeld and Gertler, 1997; Park et al., 2008; Tudor et al., 2007). Embeddedness occurs over time, favoring the stability of the IS relationships, thus enhancing the ISN sustainability over the long period, i.e., the capability to create benefits with continuity over time (Cao et al., 2009; Tudor et al., 2007).

Table 1.8. Phases of the development of self-organized ISNs.

	Boons and Baas (2004)	**Doménech and Davies (2011b)**	**Chertow and Ehrenfeld (2012)**
time	Regional efficiency	Emergence	Sprouting
	Regional learning	Probation	Uncovering
	Sustainable industrial district	Development and expansion	Embeddedness

A recent trend of the literature framed self-organized ISNs as Complex adaptive systems (CASs) (Chertow and Ehrenfeld, 2012). In fact, CASs are networks of adaptive agents that emerge over time into coherent forms through interaction, without any singular entity or central control mechanism deliberately managing or controlling the overall system (Dooley, 1997; Holland, 2002, 1995). Adaptation and self-organization are the main features of CASs. Adaption means that the system changes, improving its fitness with its environment, and creates new forms of emergent order consisting in new structures, patterns, and properties. Adaption is possible thanks to self-organization, i.e., the new order arises from the interaction among agents without being externally imposed on the system (Goldstein, 1999).

The literature recognizes that several barriers negatively affect the development of the IS approach, thus hampering the creation of both top-down and bottom-up ISNs. Fichtner et al. (2005) classified such barriers into two categories: i) barriers at the firm level; and ii) barriers at the cooperation level.

Barriers at the firm level affect the willingness of companies to implement the IS approach, which is a necessary condition for the development of the IS practice (Heeres et al., 2004). The main reason limiting such a willingness seems to be the lack of awareness of the concept of IS by firms. This refers to the insufficient understanding of IS terminologies, how to integrate the IS approach within the current business, benefits achievable, business models supporting the IS practice, dynamics of symbiotic cooperation, and potential business scenarios arising from such a cooperation (Chiu and Yong, 2004; Fichtner et al., 2005; Gibbs and Deutz, 2005; Sakr et al., 2011). In fact, firms with previous experiences of IS are able to easily create new symbiotic relationships rather than firms without similar experiences (Heeres et al., 2004; Paquin et al., 2015; Zhu and Ruth, 2014). Moreover, firms may lack of organizational capabilities needed to support the IS processes, or prefer to not change the current organizational routines (Eilering and Vermeulen, 2004; Tudor et al., 2007).

Academia, business associations, and governments play an important role in enabling firms to overcome these barriers. From one hand, academia should collaborate with business association by proposing initiatives useful to disseminate the IS approach among firms (Costa et al., 2010). In this regard, Heeres et al. (2004) offer examples of business associations that act as a platform for education and inform companies about the potential benefits stemming from the IS practice. Business associations may also serve as communication platforms between companies by providing their management and staff with important social contacts. From the other hand, the role of governments in enabling the adoption of the IS approach is acknowledged as fundamental. Political action is needed to create a business environment that promotes communication, information sharing, and cooperation among companies, universities, research institutes, and local government (Park et al., 2016). Moreover, the government can contribute to make visible to companies the benefits achievable by suggesting possible symbiotic opportunities and/or financing their feasibility studies (Costa et al., 2010; Park et al., 2008, 2016). However, the literature recognizes the lack of institutional support to promote IS projects as an additional barrier hampering the adoption of the IS approach (e.g., Alfaro and Miller, 2014).

In order to be successfully implemented, IS exchanges have to be feasible from legal, technical, and economic point of view simultaneously (Garner and Keoleian, 1995). **Barriers at the cooperation level** negatively affect these feasibility conditions, hampering the arise of new IS relationships.

From the legal point of view, two barriers may arise: i) normative impediments forbidding the use of a given waste as input; ii) too much bureaucracy required to activate IS exchanges, which discourages firms to cooperate (Costa et al., 2010; Fichtner et al., 2005; Frosch and Gallopulos, 1989; Gibbs and Deutz, 2005; Zhang et al., 2010).

However, IS relationships legally feasible may be unfeasible from the technical point of view. This is due to the lack of waste demand despite an actual supply or, *vice versa*, the lack of waste supply despite an actual demand. In fact, into a given geographic area where a given waste is generated, firms requiring that waste may lack. Similarly, into a given geographic area where a given waste is required, firms producing that waste may lack (Alfaro and Miller, 2014; Eilering and Vermeulen, 2004). Moreover, even in presence of firms producing and requiring a given waste, IS relationships may be hampered when the quality of waste is not enough to make the waste able to be used as input (Eilering and Vermeulen, 2004; Fichtner et al., 2005; Lyons, 2005). In these cases, firms prefer not implementing the IS practice because the uneven quality of wastes materials could cause damage to production equipment or negatively affect the quality of products (Deutz and Gibbs, 2008; Lowe, 1997). Moreover, a further barrier concerns the incomplete or imperfect information among firms about both quantity and quality of wastes and inputs, as well as their availability over time (Sakr et al., 2011; Zhu and Cote, 2004). Policy intervention plays an enabling/catalyzing role in helping to identify opportunities and creating the appropriate conditions for inter-firm networking to take place (Sakr et al., 2011). An additional success factor is to increase the availability of information for companies (Heeres et al., 2004). Several projects have been proposed in such a direction, aimed in particular to map all firms belonging to a given region, their geographical localization, the kind and the quantity of all required inputs and generated wastes, and to create a database including all these information, which could be available for firms, as well as a communication platform for companies (Álvarez and Ruiz-Puente, 2016; Chertow, 2007; Cutaia et al., 2014; Heeres et al., 2004; Luciano et al., 2016). In such a way, firms could have easy access to information, reducing their transaction costs. More recently, an ontological framework using semantic web was developed to support companies in the creation of IS relationships (Raafat et al., 2013; Trokanas and Cecelja, 2016). In particular, ontology models were used to represent: i) tacit knowledge, in the form of description of waste streams (material, energy, water), description of enabling technologies and description of the IS process; and ii) explicit knowledge about participating companies, in the form of IS relevant data. Moreover, the ontological framework can be integrated by semantic input–output matching, useful to discover feasible symbiotic relationships within a region, ranking them by their technological, economic and environmental benefits (Cecelja et al., 2015a, 2015b; Trokanas et al., 2014). By integrating communication platforms with these tools, each firm can be suggested about feasible symbiotic relationships that it can implement and related partners. Hence, transaction costs can be further decreased. However, the success of such an approach is constrained by the willingness of firms to share private information with other firms. Unfortunately, this seems to be a critical issue for the development of IS relationships: in fact, firms are often unwilling to share their data about typologies and quantity of produced wastes and required inputs due to lack of trust (Eilering and Vermeulen, 2004; Fichtner et al., 2005; Gibbs and Deutz, 2007; Mirata, 2004).

Finally, from the economic point of view, several barriers to the IS cooperation have been identified (Ashton, 2011; Fichtner et al., 2005; Frosch and Gallopulos, 1989; Li et al., 2015; Mirata, 2004; Sakr et al., 2011; Shi et al., 2010; Zhang et al., 2013). Of course, firms collaborate in IS relationships only if they gain economic benefits from them. However, companies may be unwilling to cooperate even if the economic convenience from such a cooperation is too low. The economic convenience can be limited by several factors. *In primis*, if waste supply is much higher than waste demand, the firm producing waste will gain low benefits from the IS relationship since only low quantity of wastes will be no more landfilled. Similarly, if waste demand is much higher than waste supply, the firm requiring waste will gain low benefits from the IS relationship since only low quantity of inputs will be no more purchased from traditional suppliers. Moreover, even in presence of a strong match between waste demand and supply, economic benefits can be limited because of low waste disposal costs and/or low input purchase costs, high investments required to create the IS relationships, and high transaction costs for the involved firms. Furthermore, symbiotic investments are often supposed to be too risky, in terms of high payback period and uncertain return on investment; therefore, firms may prefer avoiding such kind of investments. Finally, despite all firms gain enough economic benefits from the cooperation, the unfairly sharing of these benefits among the involved companies may limit their willingness to cooperate. Two kinds of policy measures have been developed to overcome these barriers: i) regulatory instruments; and ii) economic instruments. Regulations and legal frameworks compel firms to implement the IS practice, for instance banning specific wastes from landfills, thereby forcing firms to implement different strategies for their disposal (Chertow and Lombardi, 2005; Costa et al., 2010; Costa and Ferrão, 2010; Lehtoranta et al., 2011; Van Berkel et al., 2009). Economic instruments motivate firms to implement the IS practice by increasing the economic benefits stemming from the IS exchanges. Examples of these instruments are landfill taxes (Costa et al., 2010; Costa and Ferrão, 2010), economic subsidies for studying feasibility conditions of IS projects (Park et al., 2016), building facilities (Ohnishi et al., 2012), financing IS transactions (Shi et al., 2010), and fiscal incentives for firms adopting the IS practice (Mirata, 2004).

Moreover, an additional issue arises, because the economic benefits of a given firm depend on the cooperation with other firms. However, often firms relate cooperation to strategic dependence from other firms. For this reason, a given firm may choose to not cooperate with other firms, in order to not be strategically dependent on them (Ehrenfeld and Chertow, 2002; Fichtner et al., 2005).

1.3 Motivations of the study and research questions

ISNs are widely recognized as a useful tool to create economic benefits for firms as well as environmental and social benefits for the collectivity as a whole. However, such a tool is currently underdeveloped in terms of practical applications compared to theoretical opportunities because the IS approach is not fully adopted by companies. Hence, economic opportunities for firms are not exploited, thus resulting in positive externalities not created for the society. Thus, the benefits currently created by the IS practice are lower than the benefits potentially achievable. Such an issue strongly limits the efficacy of the IS approach in tackling the challenges of sustainable development. Two different phenomena contribute to the underdevelopment of the IS approach.

The former concerns the low creation rate of new self-organized ISNs. Such a phenomenon unveils the current difficulty to create new symbiotic relationships among firms, despite the great efforts by the literature in addressing the barriers hampering the development of the IS approach. In fact, a recent analysis conducted by Paquin et al. (2015) on the NISP showed that only 39% of feasible IS relationships suggested to companies was created. In particular, there are two barriers actually remaining not properly addressed or even unsolved. Clearly, the current situation reveals that the weight of these barriers on the creation of IS relationships is strong. The first issue concerns the low awareness of firms about what business models they can adopt to support the IS practice and what business scenarios can arise from collaboration among companies. Many case studies have been analyzed by the literature with the aim to disseminate successful experiences of IS, which may be a guide for firms interested to adopt the IS approach. However, general models describing the different strategies through which firms can create value and obtain economic benefits by IS are lacking. Moreover, one of the factors for the success of IS relationships is the fair distribution of economic benefits among all the involved companies. This is a complex issue, since “fair distribution” does not necessarily imply “equal distribution” (Gilbert, 2012; Negishi, 2014; US National Research Council, 1975). Despite the literature recognizes that a problem of unfair benefit sharing exists, contributions in such a direction are lacking and therefore the problem is actually not solved (Chertow et al., 2004).

The latter phenomenon contributing to the underdevelopment of the IS approach is related to the low sustainability of ISNs over the long period (Chiu and Yong, 2004). This feature refers to the capability of the ISNs to create economic and environmental benefits with continuity over time (Cao et al., 2009; Tudor et al., 2007). Several studies in the literature showed that, over time, changes in production levels of the involved firms, input purchase costs, wastes disposal costs, and additional costs arising from the IS relationship can negatively affect the feasibility conditions enabling the relationship or the willingness to cooperate of at least one involved firm (Deutz and Gibbs, 2008; Hewes and Lyons, 2008; Shi et al., 2010; Sterr and Ott, 2004). As a result, symbiotic relationships can be interrupted. In fact, the analysis conducted by Paquin et al. (2015) on the NISP showed that only 36% of created IS relationships was able to remain active over the long period. Even the interruption of one IS relationships may be critical for the overall ISN. In fact, the firm A interrupting the symbiotic relationship with firm B reduces the economic benefits that B gains from the IS approach. If the remaining benefits are not enough to motivate B to adopt the IS approach, firm B may decide to leave the ISN, interrupting all the IS relationships in which it is currently involved. This event may in turn generate a cascade effect that influences the rest of the network, reducing its capability to create benefits and hence its sustainability over the long period (Allenby and Fink, 2005; Boons and Spekkink, 2012). Whilst the literature focused on how to enhance the creation of new ISNs, few efforts have been devoted to study the sustainability of ISNs over the long period. In particular, a theoretical framework for the ISN sustainability is lacking.

In order to increase the effectiveness of the IS approach in providing benefits, it is important to tackle these two challenges simultaneously. From one hand, the creation of new self-organized ISNs should be forced by providing solutions for the unsolved barriers still hampering this practice. From the other hand, it is fundamental to ensure that ISNs would be characterized by high sustainability over the long period by developing a theoretical framework and by identifying what features of these networks can enhance such a property.

According to this framework, in order to force the adoption of the IS approach by firms, the following research questions are addressed:

- RQ1. *What are the business models that firms can adopt in order to support the implementation of the IS approach? What are the business scenarios that can arise from collaboration among firms implementing these models?*
- RQ2. *How can the economic benefits stemming from the symbiotic cooperation be fairly shared among the involved firms?*

Moreover, ISNs are considered as the analogous of the ecosystems in ecology. Ecosystems are self-organizing systems which develop towards an optimum performance for maximizing their sustainability over the long period. Such a sustainability depends on two features of the system: efficiency and resilience. The ecosystem efficiency concerns the use of natural resources to carry out the ecosystem's functions, which are responsible for providing the environment with services. The wider the set of services the ecosystem can provide by using a given set of resources, the higher the ecosystem efficiency will be (Harrington et al., 2001; Ptacnik et al., 2008; Tansky, 1976). Similarly, the lower the set of resources required to provide a given set of services, the higher the ecosystem efficiency will be. The ecosystem resilience is related to "*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*" (Walker et al., 2004). The greater the disturbance that a given ecosystem can absorb without altering its functions, the more resilient the ecosystem will be (Gunderson, 2000; Holling, 1973; Walker et al., 2004).

Very often, ecosystems do not operate at the highest efficiency that might be expected of them. In fact, there is a general tendency to sacrifice part of efficiency for more resilience to environmental changes (Brown and Ulgiati, 1997; Odum and Pinkerton, 1955; Ulanowicz et al., 2009; Ulgiati and Brown, 1998). This occurs because efficiency and resilience are inversely-related features, both depending on the structure of the ecosystem (Ulanowicz et al., 2009). In order to ensure high sustainability, the ecosystem "*must be capable of exercising sufficient directed power* [efficiency] *to maintain its integrity over time. Simultaneously, it must possess a reserve of flexible actions* [resilience] *that can be used to meet the exigencies of novel disturbances*" (Ulanowicz et al., 2009). Accordingly, too much efficient systems may have not enough resilience to perturbations, resulting unsustainable over time. Similarly, systems too much resilient may have not enough efficiency to maintain their functions over time, resulting unsustainable systems. Moreover, Ulanowicz et al. (2009) demonstrated that the sustainability of ecosystems is maximized when an optimal trade-off between efficiency and resilience is reached.

The sustainability of ISNs can be investigated by taking contributions from the ecology. In particular, I investigated the hypothesis that the efficiency in exchanging resources within the ISN and the resilience to perturbations affecting symbiotic relationships may affect the sustainability of ISNs over the long period. The literature provided few early contributions about efficiency and resilience of ISNs. In particular, both these properties lack of theoretical framework highlighting their antecedents and of numerical measures. Moreover, the literature lacks of contributions investigating efficiency and resilience in an integrated manner, since the previous contributions analyzed them separately.

Hence, the following research questions are addressed:

RQ3. *How can the concept of efficiency be contextualized for ISNs? How can numerical measures properly assessing the ISN efficiency be designed?*

RQ4. *How can the concept of resilience be contextualized for ISNs? How can numerical measures properly assessing the ISN resilience be designed?*

RQ5. *What is the role of efficiency and resilience for the ISNs sustainability? Can the ISNs sustainability be increased by proper balancing efficiency and resilience within these networks?*

For each of these research questions, one chapter is devoted. In particular, Chapter 2 addresses the RQ1, Chapter 3 addresses the RQ2, Chapter 4 addresses the RQ3, Chapter 5 addresses the RQ4, and finally Chapter 6 addresses the RQ5. Such a framework is graphically presented in Figure 1.1. Moreover, for each research question, the papers written to address it are presented in Table 1.9.

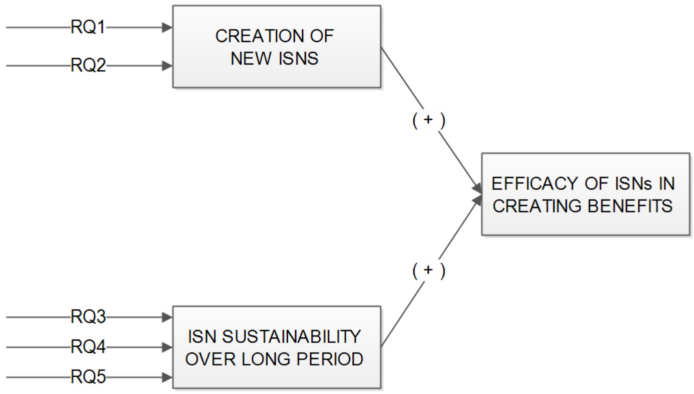


Figure 1.1. Framework proposed. From right to left: the main goal to ensure, issues affecting such a goal, research questions addressing these issues.

Table 1.9. Papers addressing the research questions investigated in this thesis.

Research question	Chapter	Publications
RQ1	Chapter 2	- Albino V., Fraccascia L. (2015). The industrial symbiosis approach: a classification of business models. *Procedia Environmental Science, Engineering and Management* 2, 217-223. - Fraccascia L., Magno M., Albino V. (2016). Business models for industrial symbiosis: a guide for firms. *Procedia Environmental Science, Engineering and Management* 3, 83-93.
RQ2	Chapter 3	- Albino V., Fraccascia L., Giannoccaro I. (2016). 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.
RQ3	Chapter 4	- Fraccascia L., Albino V., Garavelli A.C. (2017). Technical efficiency measures of industrial symbiosis network using enterprise input-output analysis, *International Journal of Production Economics* 183, 273-286. - Albino V., Fraccascia L., Savino T. (2015). Industrial symbiosis for a sustainable city: technical, economical and organizational issues. *Procedia Engineering* 118, 950-957. - Albino V., Fraccascia L., Savino T. (2015). Industrial symbiosis within cities: the influence of urban features. In: Spender D.C., Schiuma G., Albino V. (Eds.), IFKAD 2015: 10th international forum on knowledge asset dynamics: culture, innovation and entrepreneurship: connecting the knowledge dots, 1363-1377.
RQ4	Chapter 5	- Fraccascia L., Giannoccaro I., Albino V., Rethinking Resilience in Industrial Symbiosis: Conceptualizations and Measurements, *Ecological Economics* (accepted for publication).
RQ5	Chapter 6	- Fraccascia L., Yazan D.M., Albino V., Zijm H., Sustainability of Industrial Symbiosis Networks: an agent-based modeling approach, submitted to *Journal of Industrial Ecology*.

1.4 Research methodologies adopted

To address all the research questions presented in Section 1.3, I used three different methodologies.

To identify and formalize the business models that firms can adopt to implement the IS practice (Chapter 2), I used the multiple case study approach. Such a methodology is particularly well suited to research areas for which existing theory seems inadequate (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). Different cases are selected. Each case is viewed as an experiment and is analyzed in order to identify similar patterns in the attempt to confirm emerging concepts (Davis and Eisenhardt, 2011). Analyzing multiple cases allows also generalizations of the findings that can lead to some form of replication. In fact, if more cases are shown to support the same theory, replication can be claimed. The greater the number of case studies showing replication, the more robust are the research outcomes, and the greater the rigor with which a theory has been established. Such a methodology was adopted in a wide range of fields, such as social sciences (Kompier et al., 2000), neurology (Ramus et al., 2003; White et al., 2006), supply chain management (Blome and Schoenherr, 2011; Saccani et al., 2007), knowledge management (Oliver and Reddy Kandadi, 2006), innovation management (van Echtelt et al., 2008), education (Haglund and Olsson, 2008), management (Antila, 2006; Beverland and Lindgreen, 2007).

In studying how the fairly sharing of economic benefits can force the creation of ISNs (Chapter 3), I framed the self-organized ISNs as CASs and I adopted the Agent-Based Modeling (ABM) approach to analyze them. Such an approach is used to model complex systems made by autonomous decision-making entities called agents. Each agent is characterized by: i) a set of goals that has to accomplish through the interaction with the other agents and the environment; and ii) a set of rules of social engagement, driving such interactions (Bonabeau, 2002; Weiss, 1999). The interactions among agents are often complex and nonlinear. For this reason, patterns, structures, behaviors, and phenomena that are not explicitly programmed into the model can emerge from these interactions (Macal and North, 2010). Moreover, the powers of computers to explore dynamics out of the reach of pure mathematical methods (Axelrod, 1997a) makes agent-based models very important for both theory and management: in fact, through these models, researchers are able to consider aspects usually ignored in analytical models. Applications of ABM span a broad range of disciplines such as marketing (Rand and Rust, 2011), economic systems (Deissenberg et al., 2008; Tesfatsion, 2002), finance (Arthur et al., 1997; Lebaron, 2006; Samanidou et al., 2007), organizations and innovation management (Chang et al., 2006; Dawid, 2006), manufacturing (Jiao et al., 2006; Shen and Norrie, 1999), supply chains (Giannoccaro and Pontrandolfo, 2004; Swaminathan et al., 1998), social sciences (Duffy, 2006; Epstein, 2006). I used the ABM approach also to investigate the ISN sustainability (Chapter 6). In the field of ecology, it is a common opinion that a system can be considered sustainable only by observing its behavior *a posteriori* (Costanza, 1999). Accordingly, I reproduced the behavior of ISNs by adopting the simulation approach. In such a way, the sustainability of ISNs over the long periods can be assessed by simulating the ISN dynamics over the long period and measuring the benefits created over all the simulation time.

Finally, in order to contextualize the features of efficiency and resilience in the IS field (Chapters 4 and 5), I made two literature reviews analyzing fields where these features have been investigated so far: the former about efficiency in the industrial field, the latter about resilience in ecological, complex adaptive, and engineering systems. These reviews were aimed to discover definitions and antecedents of both efficiency and resilience. Then, basing on the results of these reviews, I developed the theoretical framework for efficiency and resilience of ISNs and proposed numerical measures to assess them.

Furthermore, modeling production processes and firms involved in IS relationships, as well as waste and monetary flows among them, was propaedeutic to analyze business scenarios arising from symbiotic cooperation, as well as the dynamics of ISNs as a whole. Traditionally, physical flows among firms in ISNs was modeled by adopting Material Flow Analysis (MFA) approach (Sendra et al., 2007). However, for each firm, the amount of produced wastes and required input depends on the firm's production volume: if such a volume changed over time, the symbiotic flows among firms will be affected. MFA is a static approach, not able to take into account changes in production volumes. To overcome such a problem, I used the Enterprise Input-Output (EIO) approach (Grubbstrom and Tang, 2000; Lin and Polenske, 1998) to model physical and monetary flow within ISNs. EIO models are a set of Input-Output models, which are useful to complement managerial, environmental, and financial accounting and planning systems. In fact, the EIO approach has demonstrated be very useful to analyze the industrial metabolism of single firms (Kuhtz et al., 2010; Liang et al., 2011; Tan et al., 2016), to model logistic flows among firms in complex supply chains (Albino et al., 2002; Albino and Kühtz, 2004) or industrial districts (Albino et al., 2003), with the aim to evaluate the effect of different coordination policies of materials flows on the logistics and environmental performance of an industrial district (Albino et al., 2008) or to minimize the waste and resource consumption of a manufacturing system (Xue et al., 2007). According to this approach, each production process or firm is modeled as a black box transforming production inputs into final products (outputs), which are sold in the respective markets (Figure 1.2). Such a production generates wastes, which have to be disposed of in the landfill. As for inputs, the amount of produced wastes depends on the amount of produced outputs. Moreover, the EIO approach revealed particularly useful for the IS context because it allows to easily estimate the environmental and economic benefits due to the symbiotic practice among joint production chains (Yazan, 2016; Yazan et al., 2016b).

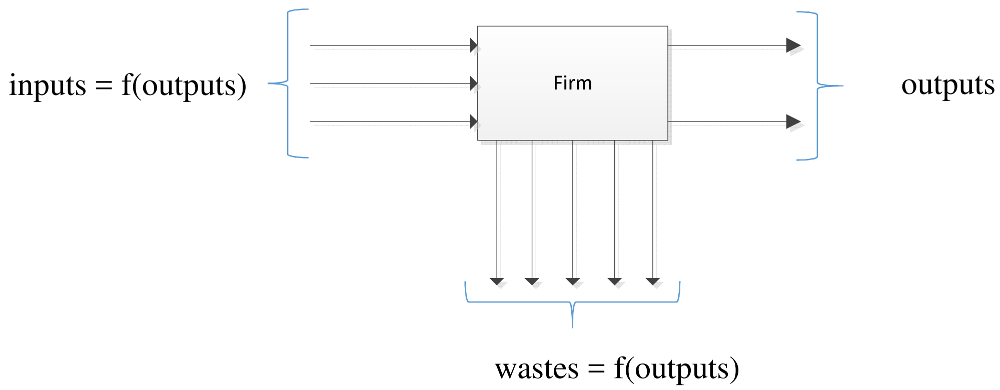


Figure 1.2. Firm modeled according to the EIO approach.

Chapter 2. Business models for industrial symbiosis

2.1 Introduction

This Chapter is aimed to identify and formalize general business models that firms can adopt to support the IS approach, as well as business scenarios that can arise by adopting these models. To achieve this goal, I analyzed the theoretical background for the concept of business model and how those based on the IS approach can be considered “sustainable business models” (Section 2.2). Then, I used an inductive approach (Eisenhardt and Graebner, 2007): I reviewed secondary literature (the academic literature presented in Chapter 1, integrated with professional literature and companies’ websites) about the implementation of IS projects and I analyzed strategies adopted by each of the involved firms. From such strategies, I formalized the correspondent business models at the firm level by adopting the framework proposed by Richardson (2008), then identifying the value proposition, the value creation, and the value capture for each business model (Section 2.3). Moreover, I analyzed business scenarios arising from the interaction among actors, each of them implementing its own business models (Section 2.4). Finally, discussion is provided (Section 2.5).

2.2 Theoretical background: The concept of business model

Business model is a concept widespread in the managerial literature and in the companies practice. It is a conceptual tool providing an abstraction of how firms do business: in particular, it reflects the firm realized strategy, highlighting the combination of production factors needed to implement such a strategy and the functions of all the involved actors. The business model serves as a strategic tool for designing business activities as well as for a comprehensive, cross-company description and analysis. Specific definitions of business models abound, each differing in their scope and conceptual focus. Some selected definitions are reported in Table 2.1.

Table 2.1. Definition of business model. Adapted from Zott et al. (2011) and Wirtz (2011).

Definition	Reference
The business model is “an architecture of the product, service and information flows, including a description of the various business actors and their role; a description of the potential benefits for the various business actors; a description of the sources of revenues”	(Timmers, 1998)
“Here, the term business model refers to the depiction of a company’s internal production and incentive system. A business model shows in highly simplified and aggregate form which resources play a role in the company and how the internal process of creating goods and services transforms these resources into marketable information, products and/or services. Therefore, a business model reveals the combination of production factors which should be used to implement the corporate strategy and the functions of the actors involved”	(Wirtz, 2000)

Table 2.1. Definition of business model. Adapted from Zott et al. (2011) and Wirtz (2011) (continued from previous page).

Definition	Reference
"A business model is simply a business model that has been put into practice. A business concept compromises four major components: Core Strategy, Strategic Resources, Customer Interface, Value Network"	(Hamel, 2000)
"Operating business models are the real thing. An operating business model is the organization's core logic for creating value. The business model of a profit oriented enterprise explains how it makes money. Since organizations compete for customers and resources, a good business model highlights the distinctive activities and approaches that enable the firm to succeed – to attract customers, employees, and investors, and to deliver products and services profitably"	(Linder and Cantrell, 2000)
"A business model is an abstraction of how a business functions. […] What the business model will do is provide a simplified view of the business structure that will act as the basis for the communication, improvements, or innovations, and define for the information system requirements that are necessary to support the business. It isn't necessary for a business model to capture an absolute picture of business or to describe every business detail. […] The evolving models also help the developers structure and focus their thinking. Working with the models increases their understanding of the business and, hopefully, their awareness of new opportunities for improving business"	(Eriksson and Penker, 2000)
The business model depicts "the content, structure, and governance of transactions designed so as to create value through the exploitation of business opportunities"	(Amit and Zott, 2001)
"A business model is comprised of four parts: a value proposition or "cluster" of value proposition, a marketspace offering, a unique and defendable resource system, and a financial model. The value proposition defines the choice of target segment, the choice of focal customer benefits, and a rationale for why the firm can deliver from benefits package significantly better than competitors. The offering entails a precise articulation of the products, services, and information that is provided by the firm. The resource system supports the specific set of capabilities and resources that will be engages in by the firm to uniquely deliver the offering. The financial model is the various ways that the firm is proposing to generate revenue, enhance value, and grow"	(Rayport and Jaworski, 2001)
"Based om the review of existing literature, I would define a business model as consisting of the following causally related components, starting at the product market level: 1) customers, 2) competitors, 3) offering, 4) activities and organization, 5) resources and 6) factor and production input suppliers. The components are all cross-sectional and can be studied at a given point in time. To make this model complete, I also include 7) the managerial and organizational, longitudinal process component, which covers the dynamics of the business model and highlights the cognitive, cultural, learning and political constraints on purely rational changes of the model"	(Hedman and Kalling, 2002)
Business models are "stories that explain how enterprises work. A good business model answer Peter Drucker's age old questions: Who is the customer? And what does the customer value? It also answers the fundamental questions every manager must ask: How do I make money in this business? What is the underlying economic logic that explains how I can deliver value to customers at an appropriate cost?"	(Magretta, 2002)
The business model is "the heuristic logic that connects technical potential with the realization of economic value"	(Chesbrough and Rosenbloom, 2002)
"A business model is a model on high abstraction level which illustrates the essential, relevant aspects of the company in an aggregate, clear form. Ideas and concepts for businesses can be identified, discussed and/or evaluated"	(Rentmeister and Klein, 2003)
"A business model is the set of which activities a firm performs, how it performs them, and when it performs the mas it uses its resources to perform activities, given its industry, to create superior customer value (low-cost or differentiated products) and put itself in a position to appropriate the value"	(Afuah, 2004)
"A business model is a conceptual tool containing a set of objects, concepts and their relationships with the objective to express the business logic of a specific firm. Therefore we must consider which concepts and relationships allow a simplified description and representation of what value is provided to customers, how this is done and with which financial consequences"	(Osterwalder et al., 2005)

Table 2.1. Definition of business model. Adapted from Zott et al. (2011) and Wirtz (2011) (continued from previous page).

Definition	Reference
A business model is a "concise representation of how an interrelated set of decision variables in the areas of venture strategy, architecture, and economics are addressed to create sustainable competitive advantage in defined markets […] It has six fundamental components. Value proposition, customer, internal process/competencies, external positioning, economic model, and personal/investor factors"	(Morris et al., 2005)
Business models "consist of four interlocking elements, that, taken together, create and deliver value. […] These are: customer value proposition, profit formula, key resources, and key processes"	(Johnson et al., 2008)
"A business model is […] a reflection of the firm realized strategy"	(Casadesus-Masanell and Ricart, 2010)
"A business model articulates the logic, the data and other evidence that support a value proposition for the customer, and a viable structure of revenues and costs for the enterprise delivering that value"	(Teece, 2010)
"A business model is a simplified and aggregated representation of the relevant activities of a company. It describes how marketable information, products and/or services are generated by means of a company's value-added component. In addition to the architecture of value creation, strategic as well as customer and market components are considered in order to realize the overriding objective of generating and preserving a competitive advantage"	(Wirtz, 2011)

Though a comprehensive review of the different definitions provided by the literature, Richardson (2008) proposed a consolidated view of three main elements that have to be addressed by a business model:

- *Value proposition*. What is the firm's basic approach to competitive advantage;
- *Value creation*. What is the source of its competitive advantage;
- *Value capture*. How the firm generates revenue and profit.

Actually, one of the key challenges to tackle the pressure of sustainable development is designing business models able to ensure that firms capture economic value for themselves through delivering social and environmental benefits (Schaltegger et al., 2016). In this regard, sustainable business models are models that "*create competitive advantage through superior customer value and contribute to a sustainable development of the company and society*" (Lüdeke-Freund, 2010). In particular, the value proposition of a sustainable business model must include positive effects for society and environment in addition to the economic value for the firm. Firms can create such a proposed value by implementing technological, organizational, and management innovations (Boons and Lüdeke-Freund, 2013). With the aim to support the development and the implementation of sustainable business models, Bocken et al. (2014) identified eight archetypes for these models, i.e., groupies of mechanisms and solutions that may contribute to building up the business models for sustainability. The archetypes are: i) maximize material and energy efficiency; ii) create value from 'waste'; iii) substitute with renewables and natural processes; iv) deliver functionality rather than ownership; v) adopt a stewardship role; vi) encourage sufficiency; vii) re-purpose the business for society/environment; and viii) develop scale-up solutions.

The IS approach can be implemented through sustainable business models classified under the archetype "create value from waste" (Bocken et al., 2014). In fact, the IS practice allows turning existing waste streams into useful and valuable inputs to other products. The sustainability of business models oriented to the IS approach stems from the environmental benefits generated for the collectivity as a whole simultaneously with the economic value created for firms.

2.3 Business models for the industrial symbiosis approach at the firm level

Two kinds of actors are involved in symbiotic relationships: waste producer and waste user (Liwarska-Bizukojc et al., 2009). In this Section, I identified business models that each kind of actor can implement.

From one side, firms producing wastes can implement the IS approach by adopting two different strategies: i) using the produced wastes within the firm (*internal exchange*); ii) sending the produced wastes to at least another firm (*external exchange*).

Internal exchange. Firms can use wastes produced by a given production process as inputs for other production processes within the firm boundaries. The value proposition of this model is related to increase the production efficiency of firms, due to the the lower amount of wastes disposed of in the landfill per unit of output generated by the firm (such an issue will be extensively discussed in Chapter 4). Such a value is created by implementing organizational innovations to manage the additional flows and stocks of wastes within the firm boundaries. Firms can capture the value in form of lower production costs, in particular due to the lower waste disposal costs. Moreover, the increased environmental sustainability of production processes may generate additional value in form of improved firm's reputation from stakeholders.

External exchange. Instead of using the produced wastes within the firm boundaries, firms can send their wastes to other firms, which will use them in their production processes. Also in this case, the value stems from increasing the production efficiency of firms (see Chapter 4). However, in such a case, the value is created by producing wastes with features making them able to be used by other firms (e.g., with adequate qualitative level). In this regard, waste treatment processes may be requested downstream waste production. Alternatively, firms cannot symbiotically connect each other (see Section 1.2). Finally, the lower production costs (in form of lower waste disposal costs) and the higher firm's reputation from stakeholders contribute to create value for firms.

Table 2.2 shows value proposition, value creation, and value capture for both the models previously presented.

Table 2.2. Value proposition, value creation, and value capture for "internal exchange" and "external exchange" models.

	Internal exchange	External exchange
Value proposition	- Higher production efficiency (lower waste from output production)	- Higher production efficiency (lower waste from output production)
Value creation	- Organizational innovation	- Producing wastes useful for other firms
Value capture	- Lower production costs - Better reputation from stakeholders	- Lower production costs - Better reputation from stakeholders

From the other side, firms using wastes can implement two different business models oriented to the IS approach: i) input replacement; and ii) co-products generation.

Input replacement. Firms can use wastes to replace inputs in their production processes. The proposed value is related to increasing production efficiency, in form of lower amount of virgin input used to produce one unit of output (see Chapter 4). Such a value can be created by innovating the production process from the technical point of view, making it able to use the waste as input. In this regard, waste treatment processes may be requested upstream waste use. Finally, the value is captured through lower production costs, in the form of lower virgin input purchase costs. Moreover, also in this case, the improved environmental efficiency may generate additional value, in form of better reputation from stakeholders.

Co-product generation. Firms exploit wastes to generate at least one new product, different to those currently generated, destined to be sold on the market. Two kinds of new products can be generated: i) products whose production phase is more environmentally sustainable than traditional products, *ceteris paribus* (an example is provided in Section 2.4.3); ii) products with some features better than traditional products, *ceteris paribus* (an example is provided in Section 2.4.4). Therefore, both these products can be considered as "differentiate products", more profitable that the traditional one. The proposed value is related to the business enlargement allowed by the IS approach, since the new products are added to the current product portfolio. So that such a value is created, the firm needs to implements product and process innovation. In fact, the firm has to design how to integrate wastes within new products and how to make production processes able to use these wastes. The created value is captured by gains from selling these new products.

Table 2.3 shows value proposition, value creation, and value capture for all the models previously presented.

Table 2.3. Value proposition, value creation, and value capture for "input replacement" and "co-products generation" models.

	Input replacement	Co-product generation
Value proposition	- Higher production efficiency (lower virgin input to produce output)	- Business enlargement
Value creation	- Process innovation	- Product innovation - Process innovation
Value capture	- Lower production costs - Better reputation from stakeholders	- Gains from selling new products

2.4 Business scenarios arising from the interaction among actors

From the interaction among actors producing wastes and firm using wastes, each of them implementing its own business model, four business scenarios may arise. All these scenarios are presented in the following sub-sections. I firstly characterized each of them in terms of physical and monetary flows among firms and production processes involved. In describing these flows, I adopted the EIO approach. Then, from the analysis of these flows, I identify strengths and weaknesses related to the implementation from both the strategic and organizational point of view. Moreover, a short case study representative for the business scenario is presented.

2.4.1 "Internal exchange to input replacement" scenario

This scenario arises when wastes are used within the firm's boundaries to replace production inputs. As an example, McDonald's UK produces biodiesel from the used cooking oil generated in its kitchens. The biodiesel so produced is used to fuel the company delivery vehicle. In 2013, 3.7 million liters of used cooking oil were converted in 3.1 million liters of biodiesel, fueling around 42% of the company delivery fleet. Hence, both fried oil disposal costs and fuel purchase costs are reduced.

Let us consider two production processes, A1 and A2, belonging to generic firm A. For the sake of simplicity, let us assume that each process (A1 and A2) produces only one output (*j1* and *j2* for A1 and A2, respectively), uses only one input (*l1* and *l2*, respectively), and generates only one waste (*k1* and *k2*, respectively). Moreover, let us assume that production processes produce two different outputs, responding to a market demand: hence, the amount of outputs produced is driven by the demand from the external markets, where these products are sold. According to the EIO approach, the amount of produced outputs drives the amount of input needed for production. In particular, it results:

$$\begin{aligned} r_{l1-A1} &= R_{l1-j1} \cdot x_{j1-A1} \\ r_{l2-A2} &= R_{l2-j2} \cdot x_{j2-A2} \end{aligned} \tag{2.1}$$

where x_{j1-A1} and x_{j2-A2} denote the amount of outputs *j1* and *j2* produced by process A1 and A2, respectively, r_{l1-A1} and r_{l2-A2} denote the amount of inputs *l1* and *l2* required produced by process A1 and A2, respectively, R_{l1-j1} and R_{l2-j2} denote the amount of input *l1* and *l2* required to produce one unit of output *j1* and *j2*, respectively.

Similarly, the amount of wastes generated is dependent on the amount of produced output. It results:

$$\begin{aligned} w_{k1-A1} &= W_{k1-j1} \cdot x_{j1-A1} \\ w_{k2-A2} &= W_{k2-j2} \cdot x_{j2-A2} \end{aligned} \tag{2.2}$$

where w_{k1-A1} and w_{k2-A2} denote the amount of wastes *k1* and *k2* required produced by process A1 and A2, respectively, W_{k1-j1} and W_{k2-j2} denote the amount of wastes *k1* and *k2* required to produce one unit of output *j1* and *j2*, respectively.

The EIO approach is also useful to assess the firms' production costs. Such a cost (pc_A) is computed by using the following equation:

$$\begin{aligned} pc_A = upc_{l1-A1} \cdot r_{l1-A1} + upc_{l2-A2} \cdot r_{l2-A2} + udc_{k1-A1} \cdot w_{k1-A1} + udc_{k2-A2} \cdot w_{k2-A2} \\ = \left(upc_{l1-A1} \cdot R_{l1-j1} + udc_{k1-A1} \cdot W_{k1-j1}\right) \cdot x_{j1-A1} \\ + \left(upc_{l2-A2} \cdot W_{k2-l2} + udc_{k2-A2} \cdot W_{k2-l2}\right) \cdot x_{l2-A2} \end{aligned} \tag{2.3}$$

where upc_{l1-A1} and upc_{l2-A2} denote the unit purchase costs [€/unit] of inputs *l1* and *l2*, respectively, and udc_{k1-A1} and udc_{k2-A2} denote the unit disposal costs [€/unit] of wastes *k1* and *k2*, respectively.

Let us consider now that waste *k1* is used to replace input *l2*. Moreover, let us assume that one unit of *k1* is able to replace $s_{k1 \to l2}$ units of *l2*. The amount of waste that can be exchanged between processes A1 and A2 ($e_{A1 \to A2}$) can be computed by using the following equation:

$$e_{A1 \to A2} = min\left\{w_{k1-A1}; \frac{r_{l1-A2}}{s_{k1 \to l2}}\right\} \tag{2.4}$$

In fact, $e_{A1 \to A2}$ cannot be higher than either the amount of waste *k1* produced and the amount of waste needed to replace r_{l1-A2} units of input.

In this regard, three different conditions can arise: i) $e_{A1 \to A2} = w_{k1-A1} < \frac{r_{l1-A2}}{s_{k1 \to l2}}$. In this case, waste supply is lower than the corresponding waste demand. Hence, the overall amount of waste *k1* produced by process A1 is used by process A2 to replace the input *l2* and no units of waste *k1* have to be disposed of in the landfill. However, $r_{l1-A2} - (s_{k1 \to l2} \cdot e_{A1 \to A2})$ units of input A2 have to be purchased from the external market; ii) $e_{A1 \to A2} = \frac{r_{l1-A2}}{s_{k1 \to l2}} < w_{k1-A1}$. In this case, waste supply is higher than the correspondent waste demand. Hence, the overall amount of input *l2* required by process A2 is replaced by waste *k1* from process A1 and no units of input *l2* have to be purchased from the external market. However, $w_{k1-A1} - e_{A1 \to A2}$ units of waste A1 have to be disposed of in the landfill; and iii) $e_{A1 \to A2} = w_{k1-A1} = \frac{r_{l1-A2}}{s_{k1 \to l2}}$. In this case, waste supply is equal to waste demand. The overall amount of waste *k1* is used to replace the input *l2* and, at the same time, the overall amount of input *l2* is replaced by waste *k1*. Hence, in such a condition, the firm does not dispose of in the landfill any unit of waste and does not purchase any unit of input from the external market.

Moreover, the economic benefits stemming from the symbiotic exchange can be quantified. The gross economic benefits stem from lower input purchase costs and lower waste disposal costs. In fact, when $e_{A1 \to A2}$ units of waste *k1* are exchanged between processes A1 and A2, the firm reduces its waste disposal costs of $udc_{k1-A1} \cdot e_{A1 \to A2}$ euros and its input purchase costs of $upc_{l2-A2} \cdot s_{k1 \to l2} \cdot e_{A1 \to A2}$ euros. However, additional costs may arise from the IS practice. In such a case, waste treatment costs arise when the waste needs to be treated in order to be make available to be used as input. The total treatment costs ($rc_{k1\to l2}$) can be computed by using the following equation:

$$rc_{k1\to l2} = urc_{k1\to l2} \cdot e_{A1\to A2} \tag{2.5}$$

where $urc_{k1\to l2}$ is the cost to treat one unit of waste [€/unit].

Table 2.4 resumes the gross economic benefits as well as the additional costs due to IS.

Table 2.4. Gross economic benefits and additional costs due to IS for firm A.

Gross economic benefits due to IS [€]	
Reduction in waste disposal cost	$udc_{k1-A1} \cdot e_{A1\to A2}$
Reduction in input purchase cost	$upc_{l2-A2} \cdot s_{k1\to l2} \cdot e_{A1\to A2}$
Additional costs due to IS [€]	
Waste treatment costs	$urc_{k1\to l2} \cdot e_{A1\to A2}$

Both production processes A1 and A2, the physical flows from and to each process, the waste exchange between processes, and the monetary flows from and to the firm are graphically depicted in Figure 2.1.

Strengths. As the main strength of this model, no cooperation with partners is required. It means that the firm does not need to disclose personal information or to negotiate the economic terms of the relationship (e.g., how additional costs have to be shared among firms), which is one of the strongest barrier hampering the adoption of the IS practice Moreover, in the phase of input replacement, the firm is strategically independent because the amount of wastes that it can use does not depend on any other firm. In fact, Equation 2.3 can be written as $e_{A1\to A2} = min\left\{W_{k1-j1} \cdot x_{j1-A1}; \frac{R_{l2-j2} \cdot x_{j2-A2}}{s_{k1\to l2}}\right\}$, resulting that $e_{A1\to A2} = f(x_{j1-A1}, x_{j2-A2})$. Finally, from the economic point of view, two issues can be highlighted: i) the firm does not sustain any waste transportation costs; ii) the benefits from the IS approach have not to be shared with other firms.

Weaknesses. Symbiotic exchanges within the firm's boundaries may be limited in the case of low diversity among production processes, not enough to allow technical match among wastes and inputs (Korhonen, 2001a). Moreover, from the economic point of view, the additional costs needed to activate symbiotic exchanges cannot be shared with any partner. Therefore, this model may be difficult to implement for small firms.

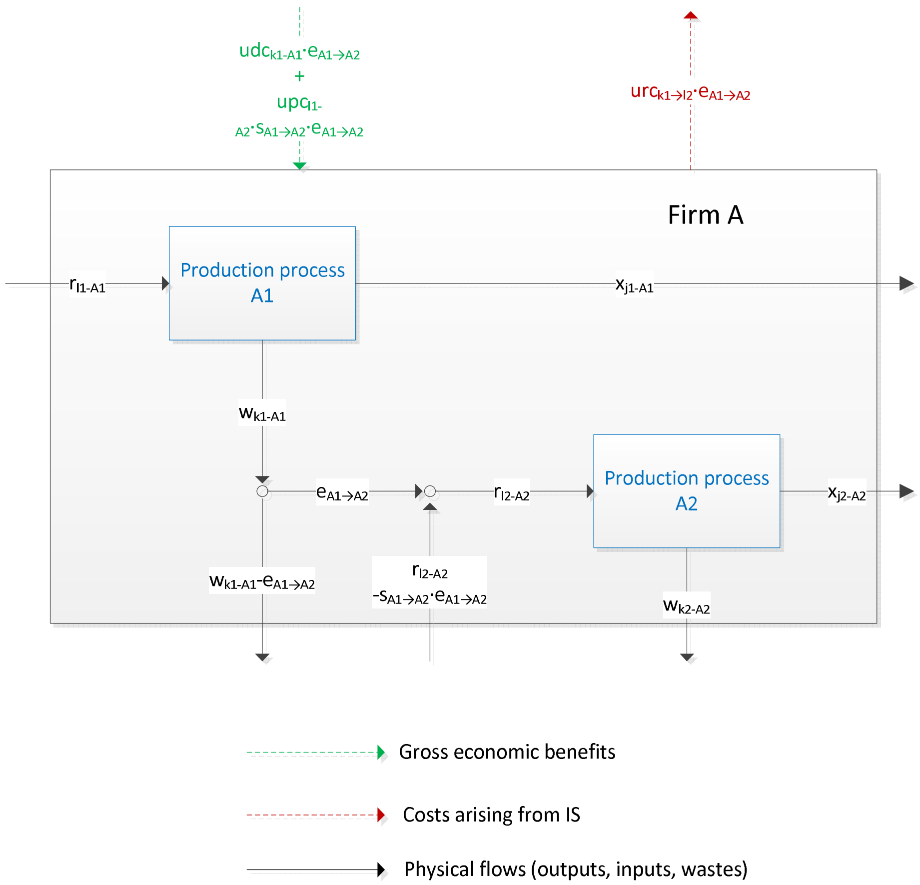


Figure 2.1. Physical flows from and to each process, waste exchange among processes, and monetary flows from and to the firm.

2.4.2 "External exchange to input replacement" scenario

This scenario arises when at least one waste generated by a firm is used to replace at least one input in another firm. Since the "external exchange" is the most adopted business model by firms producing wastes, as well as the "input replacement" is the most adopted business model by firms requiring wastes, this business scenario is the most common. As an example, I quote the symbiotic relationship between DENSO Manufacturing UK and Mir-Ver Metals, implemented under the NISP in the UK. DENSO Manufacturing UK produces automotive air conditioning units and engine cooling systems for the automotive industry. Related production processes generate potassium aluminum fluoride as hazardous waste. Instead of being landfilled, such a waste is used by Mir-Ver Metals, a company working in the metal industry, as inputs for its production processes. Cooperation between these firms allows to divert from landfill 15 tons of waste per year, reducing production costs by 45.000 euro.

Let us consider two firms A and B. For the sake of simplicity, let us assume that each firm produces only one output (*j1* and *j2* for A and B, respectively), uses only one input (*l1* and *l2*, respectively), and generates only one waste (*k1* and *k2*, respectively). It results:

$$r_{l1-A} = R_{l1-j1} \cdot x_{j1-A}$$
$$r_{l2-B} = R_{l2-j2} \cdot x_{j2-B} \tag{2.6}$$

where x_{j1-A} and x_{j2-B} denote the amount of outputs *j1* and *j2* produced by firms A and B, respectively, r_{l1-A} and r_{l2-B} denote the amount of inputs *l1* and *l2* produced by firms A and B, respectively, R_{l1-j1} and R_{l2-j2} denote the amount of input *l1* and *l2* required to produce one unit of output *j1* and *j2*, respectively.

Similarly, the amount of wastes generated is dependent on the amount of produced output. It results:

$$w_{k1-A} = W_{k1-j1} \cdot x_{j1-A}$$
$$w_{k2-B} = W_{k2-j2} \cdot x_{j2-B} \tag{2.7}$$

where w_{k1-A} and w_{k2-B} denote the amount of waste *k1* and *k2* required by firms A and B, respectively, W_{k1-j1} and W_{k2-j2} denote the amount of input *l1* and *l2* required to produce one unit of output *j1* and *j2*, respectively.

Production costs of each firm can be computed by using the following equations:

$$pc_A = upc_{l1-A} \cdot r_{l1-A} + udc_{k1-A} \cdot w_{k1-A}$$
$$= \left(upc_{l1-A} \cdot R_{l1-j1} + udc_{k1-A} \cdot W_{k1-j2}\right) \cdot x_{j1-A} \tag{2.8}$$

$$pc_B = upc_{l2-B} \cdot r_{l2-B} + udc_{k2-B} \cdot w_{k2-B} \tag{2.9}$$
$$= \left(upc_{l2-B} \cdot R_{l2-j2} + udc_{k2-B} \cdot W_{k2-l2}\right) \cdot x_{j2-B}$$

where, similarly to the Equation 2.3, upc_{l1-A} and upc_{l2-B} denote the unit purchase costs [€/unit] of inputs A and B, respectively, udc_{k1-A} and udc_{k2-B} denote the unit disposal costs [€/unit] of waste A and B, respectively.

Let us consider now that waste *k1* produced by firm A is used by firm B to replace input *l2*. An IS relationship arises between firms when such an exchange is implemented. Let us assume that one unit of waste *k1* is able to replace $s_{k1\rightarrow l2}$ units of input B. The amount of waste which can be exchanged between A and B ($e_{A\rightarrow B}$) can be computed by using the following equation:

$$e_{A\rightarrow B} = min\left\{w_{k1-A}; \frac{r_{l2-B}}{s_{k1\rightarrow l2}}\right\} \tag{2.10}$$

In particular, $e_{A\rightarrow B}$ cannot be higher than nor the amount of waste *k1* generated nor the amount of input *l2* required.

Similarly to the previous case, three different conditions can arise: i) $e_{A \to B} = w_{k1-A} < \frac{r_{l2-B}}{s_{k1 \to l2}}$. In this case, waste supply is lower than the corresponding waste demand. Hence, the overall amount of waste produced by firm A is used by firm B to replace its input and no units of waste *k1* have to be disposed of in the landfill. However, $r_{l2-B} - (s_{k1 \to l2} \cdot e_{A \to B})$ units of input B have to be purchased from the external market; ii) $e_{A \to B} = \frac{r_{l2-B}}{s_{k1 \to l2}} < w_{k1-A}$. In this case, waste supply is higher than the correspondent waste demand. Hence, the overall amount of input *l2* required by firm B is replaced by waste *k1* from firm A and no units of input *l2* have to be purchased from the external market. However, $w_{k1-A} - e_{A \to B}$ units of waste A have to be disposed of in the landfill; and iii) $e_{A \to B} = w_{k1-A} = \frac{r_{l2-B}}{s_{k1 \to l2}}$. In this case, waste supply is equal to waste demand. The overall amount of waste *k1* produced by firm A is used to replace input *l2* by firm B and, at the same time, the overall amount of input required by B is replaced by waste from firm A. Hence, in such a condition, firm A does not dispose of in the landfill any unit of waste *k1* and firm B does not purchase any unit of input *l2* from the external market. Black continuous lines in Figure show input, output, and waste flows between, from, and to A and B.

When two firms cooperate in exchanging wastes, the economic benefits stemming from such a cooperation can be quantified. The gross economic benefits stem from lower input purchase costs and lower waste disposal costs. In fact, when $e_{A \to B}$ units of waste are exchanged between firms A and B, the firm A (waste producer) reduces its waste disposal costs of $udc_{k1-A} \cdot e_{A \to B}$ euros whereas the firm B (waste user) reduces its input purchase costs of $upc_{l2-B} \cdot s_{k1 \to l2} \cdot e_{A \to B}$ euros.

Similarly to the previous case, waste treatment cost ($rc_{k1 \to l2}$) can arise, needed to make waste *k1* suitable to be used as input. Waste treatment cost can be computed by using the following equation:

$$rc_{k1 \to l2} = urc_{k1 \to l2} \cdot e_{A \to B} \tag{2.11}$$

Moreover, in such a case, two additional costs, eroding the gross economic benefits, arise with the IS relationship: waste transportation cost and transaction costs of cooperation (Esty and Porter, 1998; Sinding, 2000).

Transportation costs are needed to deliver the waste from the firm producer to the firm user. In the case of IS relationship between firms A and B, the total transportation costs ($tc_{A \to B}$) can be computed by using the following equation:

$$tc_{A \to B} = utc_{A \to B} \cdot d_{AB} \cdot e_{A \to B} \tag{2.12}$$

where $utc_{A \to B}$ is the cost to transport one unit of waste per kilometer [€/(unit*Km)] and d_{AB} is the distance between firms A and B [Km].

The overall costs due to waste treatment and transportation can be: i) all sustained by firm A; ii) all sustained by firm B; and iii) shared between A and B. Let λ_{AB} be the percentage of these costs sustained by the firm A. The value of λ_{AB} for each of the previous case is depicted in Table 2.5.

Table 2.5. Different cost sharing policy that firm can use in exchanging wastes.

Case	**Costs sharing**
$\lambda_{AB} = 1$	Firm A pays all the costs arising from IS
$\lambda_{AB} = 0$	Firm B pays all the costs arising from IS
$0 < \lambda_{AB} < 1$	Costs arising from IS are shared among firms

Finally, transaction costs arise in the form of search costs, negotiation costs, and enforcement costs (Chertow and Ehrenfeld, 2012). Let $cc_{A\to B}$ be transaction costs arising for firm A by the cooperation with firm B and $cc_{B\to A}$ the transaction cost arising for B from the cooperation with firm A. Both of these costs are specific for each involved firm and do not depend on the amount of exchanged wastes. Gross economic benefits and additional costs due to IS for firms A and B are resumed in Table 2.6.

Table 2.6. Gross economic benefits and additional costs due to IS for firms A and B.

Firm A	**Gross economic benefits due to IS [€]**	
	Reduction in waste disposal cost	$udc_{k1-A} \cdot e_{A\to B}$
	Additional costs due to IS [€]	
	Treatment costs	$\lambda_{AB} \cdot urc_{k1\to l2} \cdot e_{A\to B}$
	Transportation costs	$\lambda_{AB} \cdot utc_{A\to B} \cdot d_{AB} \cdot e_{A\to B}$
	Transaction costs	$cc_{A\to B}$
Firm B	**Gross economic benefits due to IS [€]**	
	Reduction in input purchase costs	$upc_{l2-B} \cdot s_{k1\to l2} \cdot e_{A\to B}$
	Additional costs due to IS [€]	
	Treatment costs	$(1-\lambda_{AB}) \cdot urc_{k1\to l2} \cdot e_{A\to B}$
	Transportation costs	$(1-\lambda_{AB}) \cdot utc_{A\to B} \cdot d_{AB} \cdot e_{A\to B}$
	Transaction costs	$cc_{B\to A}$

Dotted lines in Figure 2.2 show monetary flows from and to each firm: green lines denote ceasing costs (gross economic benefits) whereas red lines denote additional costs. Moreover, black lines denote monetary flows between firms (when a firm pays the other).

Strengths. Generally, one waste can replace more than one input, as well as one input can be replaced by more than one waste. In such a case, the symbiotic opportunities grow exponentially with the increase in the number of produced wastes and required inputs in a given geographic area. For this reason, such a scenario allows the creation of complex ISNs, where each firm can be involved in more symbiotic relationships with different firms. Moreover, potential additional costs arising from IS can be shared among firms: for this reason, such a model could be easily implemented even by small firms.

Weaknesses. Transportation and transaction costs arise from inter-firm cooperation, eroding the gross economic benefits created by using wastes in place of inputs. Moreover, firms need to find economic agreements related to waste exchange and to negotiate the cost-sharing policy. Cooperation among firms in fundamental for the success of this model. In fact, the literature shows cases where the lack of cooperation resulted in the interruption of the IS relationships (Hewes and Lyons, 2008; Lambert and Boons, 2002). Moreover, the willingness to cooperate may be limited by mismatches between demand and supply of wastes. When $e_{A\to B} \ll w_{k1-A}$ (supply much higher than demand), the firm A could be not interest to cooperate with firm B. Alternatively, when $e_{A\to B} \ll \frac{r_{l2-B}}{s_{k1\to l2}}$ (demand much higher than supply), the firm B could have low willingness to cooperate with firm A.

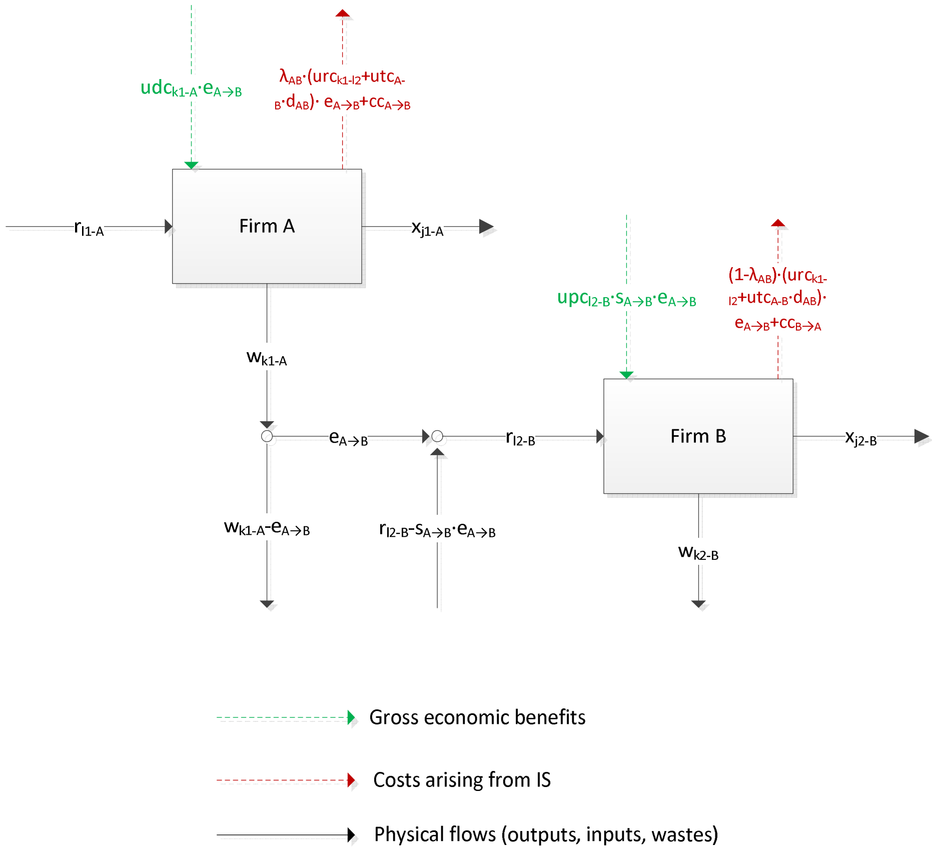


Figure 2.2. Physical and monetary flows from, to, and between two firms exchanging wastes.

2.4.3 "Internal exchange to co-product generation" scenario

This scenario arises when wastes are exploited to create new products within the firm's boundaries. Guitang Group, the largest sugar farm in China, has successfully applied this scenario. The group has exploited wastes from sugar production processes (molasses, bagasse, filtered sludge) to create new production chains (alcohol, paper, fertilizer) within the group boundaries. By implementing such an approach, from 1997 to 2004 Guitang Group increased its revenues by 153% (from 807 to 2.045 million CNY), due to the new products sold on the market, and its profit by 5.521% (from 3 to 170 million CNY), due to lower production costs and waste disposal costs (Yang and Feng, 2008).

Let us consider the production process A1 belonging to the firm A. For the sake of simplicity, let us assume that such a process produces output *j1*, requires input *l1*, and generates waste *k1*. The amount of input required and waste produced can be modeled by Equation 2.1 and Equation 2.2. Let us assume now that waste *k1* can be transformed into a new product, which can be sold on the market. Hence, the new production process A2 is implemented within the firm and the new product *l2* is generated. Let y_{j2-A2} be the amount of product *j2* that can be generated. It results:

$$y_{j2-A2} = T_{j2-k1} \cdot e_{A1\rightarrow A2} \tag{2.13}$$

where T_{j2-k1} denotes how many units of product *j2* can be generated by exploiting one unit of waste *k1*. In turn, $e_{A1\rightarrow A2}$ can be computed by the following equation:

$$e_{A1\rightarrow A2} = \begin{cases} w_{k1-A1} & if \quad f_{j2} \geq T_{j2-k1} \cdot w_{k1-A1} \\ \dfrac{f_{j2}}{T_{j2-k1}} & if \;\; f_{j2} < T_{j2-k1} \cdot w_{k1-A1} \end{cases} \tag{2.14}$$

where $T_{j2-k1} \cdot w_{k1-A1}$ is the highest amount of product *j2* that can be generated by firm A and f_{j2} is the market demand of the product *j2*. In particular, if the market demand of the new product is higher or equal than the highest amount of *j2* that can be generated by firm A ($f_{j2} \geq T_{j2-k1} \cdot w_{k1-A1}$), all the produced waste *k1* will be sent to process A2. Alternatively, only part of the waste *k1* will be sent to process A2 and the remaining $w_{j1-A1} - e_{A1\rightarrow A2}$ units of waste will be disposed of in the landfill. Two kinds of economic benefits can be recognized for the firm A: i) lower production costs in form of lower waste disposal costs ($udc_{k1-A1} \cdot e_{A1\rightarrow A2}$, where udc_{k1-A1} is the cost to dispose of in the landfill one unit of waste *k2*); ii) additional revenues by selling the new product ($p_{j2} \cdot y_{j2-A2}$, where p_{j2} is the market price of the new product). Moreover, additional costs may arise in form of treatment cost of waste *k1*. It results:

$$rc_{k1\rightarrow j2} = urc_{k1\rightarrow j2} \cdot e_{A1\rightarrow A2} \tag{2.15}$$

All these costs are resumed in Table 2.7. Gross economic benefits and additional costs due to IS for firm A. Production processes as well as physical and monetary flows are depicted in Figure 2.3.

Table 2.7. Gross economic benefits and additional costs due to IS for firm A.

Gross economic benefits due to IS [€]	
Reduction in waste disposal cost	$udc_{k1-A1} \cdot e_{A1\rightarrow A2}$
Additional revenues by selling the new product	$p_{j2} \cdot y_{j2-A2}$
Additional costs due to IS [€]	
Treatment costs	$urc_{k1\rightarrow j2} \cdot e_{A1\rightarrow A2}$

Strengths. As in the scenario "internal exchange to input replacement" (Section 2.4.1), no cooperation with partners is required. Moreover, notice that the waste needed to produce the new product is generated within the firm's boundaries; in fact, from Equations 2.13 and 2.14, it results that $y_{j2-A2} = f(x_{j1-A1})$. This makes the new product generation independent on contributions from other firms. Such a strength is particularly relevant, because without the waste the new product cannot be generated.

Weaknesses. This model suffers from all the weaknesses of the previous one. Moreover, since the amount of new products that can be generated depends on the available amount of wastes (Equations 2.13 and 2.14), firms would be unable to satisfy demand of new products exceeding the highest amount that can be produced $(f_{j2} - y_{j2-A2})$. Therefore, business opportunities cannot be exploited.

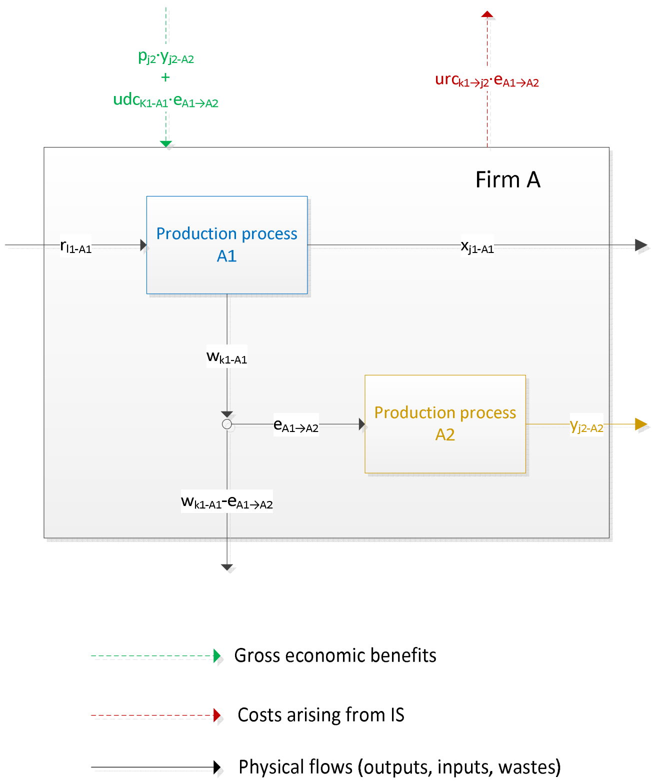


Figure 2.3. Physical flows from and to each process, waste exchange among processes, and monetary flows from and to the firm.

2.4.4 "External exchange to co-product generation" scenario

This scenario arises when wastes from a given firm are exploited by another firm to create additional products to its main business. As an example of such a scenario, the case of CSC can be adduced. CSC is an Italian firm producing and supplying concrete to the local construction industry. Since the financial crisis in 2008 negatively affected the firm business by reducing final demand of its products, the firm decided to introduce new products within its current portfolio in order to enter in new market segments and increase revenues. It developed a new concrete product that mixes a percentage of chopped plastic into the concrete mix in place of conventional aggregate. In fact, plastic is 50% less weight than aggregate and has positive performance about impact resistance and noise absorption. Moreover, plastic used for concrete production stems from urban wastes. CSC founded a joint venture company collecting urban wastes, in order to reduce supply risk by directly managing the supply chain. By adopting this model, CSC reduced its production costs because of lower amount of virgin aggregates used in concrete production, increased its revenues by selling the new product, and finally obtained additional gains because of payment from the municipality for managing the waste (Short et al., 2014).

Let us consider firms A and B. Firm A produces output *j1*, requires input *l1*, and generates waste *k1*. Firm B currently implements the production process B1, which generates output *j2* and requires input *l2*. Let us assume that firm B implements the new production process B2 to produce the additional product *j3* by exploiting waste *k1*. The amount of *j3* produced depends on the amount of waste *k1* exchanged between the firms:

$$y_{j3-B2} = T_{j3-k1} \cdot e_{A \to B2} \qquad (2.16)$$

where T_{j3-k1} denotes how many units of products *j3* can be generated by exploiting one unit of waste *k1*. In turn, $e_{A \to B2}$ can be computed as the minimum between the amount of *k1* offered by firm A to firm B (w_{k1-A}) and the amount of *k1* required by firm B to firm A ($D_{A \to B2}$). It results:

$$e_{A \to B2} = \min\{w_{k1-}; D_{A \to B2}\} \qquad (2.17)$$

where, $D_{A \to B}$ can be computed by using the following equation:

$$D_{A \to B2} = \begin{cases} w_{k1-A} & if \quad f_{j3} \geq T_{j3-k1} \cdot w_{k1-A} \\ \dfrac{f_{j3}}{T_{j3-k1}} & if \;\; f_{j3} < T_{j3-k1} \cdot w_{k1-A} \end{cases} \qquad (2.18)$$

$T_{j3-k1} \cdot w_{k1-A}$ is the highest amount of product *j3* that can be generated by firm B. In particular, if the market demand of the new product (f_{j3}) is higher or equal than such a quantity, all the produced *k1* will be sent to the process B2. Alternatively, only part of produced *k1* will be sent to process B2 and the remaining $w_{k1-A} - e_{A\to B2}$ units of waste will be sent to other firms or disposed of in the landfill.

From the economic point of view, firm A reduces its production costs of $udc_{k1-A} \cdot e_{A\to B2}$ euros whereas firm B obtains additional revenues ($p_{j3} \cdot y_{j3-B2}$, where p_{j3} is the market price for product *j3*) from selling the new product. Moreover, additional costs may arise in form of treatment and transportation cost of waste *k1*, as well as in form of transaction costs. It results:

$$rc_{A\to B2} = urc_{k1\to j3} \cdot e_{A\to B3} \tag{2.19}$$

$$tc_{A\to B2} = utc_{A\to B} \cdot d_{AB} \cdot e_{A\to B2} \tag{2.20}$$

where $urc_{A\to B2}$ is the cost to treat one unit of waste *k1*, $utc_{A\to B}$ is the cost to transport one unit of waste from firm A to firm B, and d_{AB} is the distance between firms. Table 2.8 shows the gross economic benefits and the additional costs for each firm. All the cost sharing policies depicted in Table 2.5 can be adopted also in this case. Production processes, physical and monetary flows are depicted in Figure 2.4.

Table 2.8. Gross economic benefits and additional costs due to IS for firms A and B.

Firm A	**Gross economic benefits due to IS [€]**	
	Reduction in waste disposal cost	$udc_{k1-A} \cdot e_{A\to B2}$
	Additional costs due to IS [€]	
	Treatment costs	$\lambda_{AB} \cdot urc_{k1\to j3} \cdot e_{A\to B2}$
	Transportation costs	$\lambda_{AB} \cdot utc_{A\to B} \cdot d_{AB} \cdot e_{A\to B3}$
	Transaction costs	$cc_{A\to B}$
Firm B	**Gross economic benefits due to IS [€]**	
	Additional revenues from selling the new product	$p_{j3} \cdot y_{j3-B2}$
	Additional costs due to IS [€]	
	Treatment costs	$(1-\lambda_{AB}) \cdot urc_{k1\to j3} \cdot e_{A\to B2}$
	Transportation costs	$(1-\lambda_{AB}) \cdot utc_{A\to B} \cdot d_{AB} \cdot e_{A\to B2}$
	Transaction costs	$cc_{B\to A}$

Strengths. This model may support cooperation among firms belonging to very different sectors (that would be unable to cooperate otherwise), playing an important role in enhancing environmental innovations (Mirata and Emtairah, 2005). Moreover, additional costs from the IS relationship can be shared.

Weaknesses. As highlighted in the "internal exchange to co-product generation" scenario (Section 2.4.3), the amount of new products generated is dependent on the amount of available wastes (Equations 2.16, 2.17, and 2.18). In this case, the amount of available wastes may also depend on cooperation among firms. In the case of lack of cooperation, if the symbiotic relationship is interrupted, firm using wastes will no more be able to produce its new products. Hence, the structure of bargaining power among firms could be unbalanced (Yazan et al., 2012). Moreover, in case the waste should have fixed qualitative level to be used in new product generation, it may be difficult for firm using waste to find an adequate waste supplier. Finally, high R&D investments may be needed to create the new product.

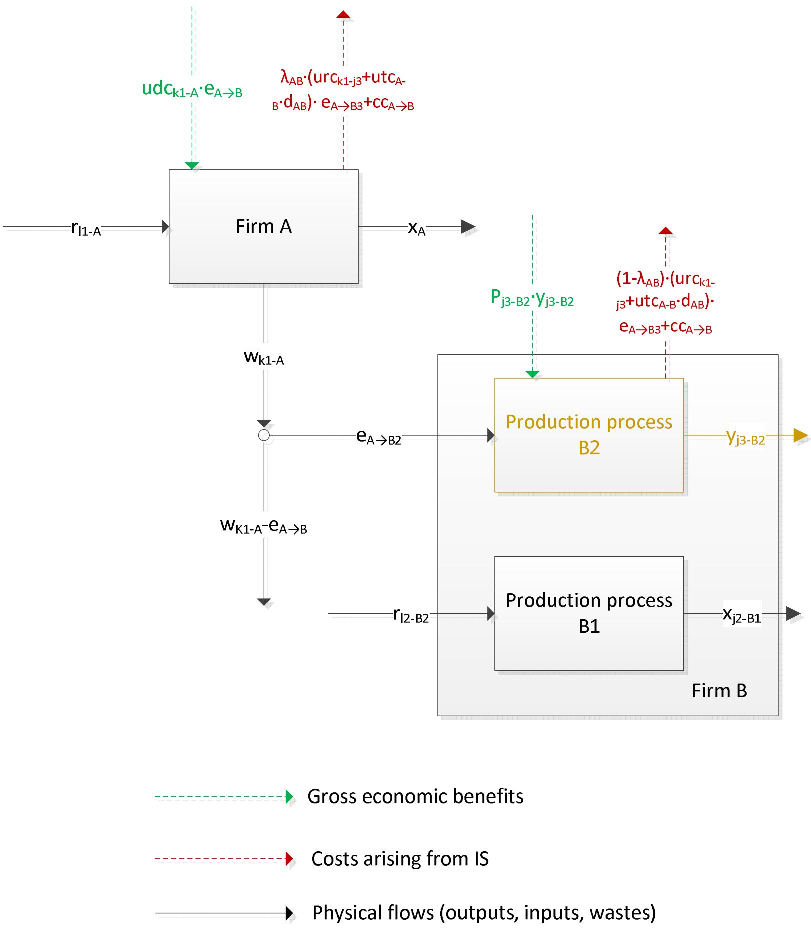


Figure 2.4. Physical and monetary flows from, to, and between two firms exchanging wastes.

2.5 Discussion

Firms can adopt the IS approach by implementing different business models. In particular, firms producing wastes can use them within the firm's boundaries or send them to other firms. Firms using wastes can use them in place of primary inputs or exploit them to generate new products. For each business model, value proposition, value creation, and value capture have been highlighted. These results contribute to fill the gap in the literature concerning the lack of general business models sustaining the IS practice. Firms can use these models to discover how the IS approach can create value for them and how to implement such an approach, contributing to the sustainable development of the society. Firms create value for themselves in form of economic benefits. Whilst reduction in production costs and revenue increase can be easily measured, it may be difficult to the higher reputation from stakeholders in economic terms. However, the literature agrees in recognizing the positive role of high environmental reputation by customers in increasing revenues (Chen and Chai, 2010; D'Souza et al., 2006; Prakash, 2002). From the combination of business models, four different business scenarios may arise. Table 2.9 resumes all these scenarios, highlighting strength and weaknesses. These scenarios can be useful for firms in discovering opportunities for adopting the IS practice.

In this regard, the choice of what model/scenario to implement may be affected by at least three factors: i) technical factors; ii) economic factors; and iii) strategical factors.

From the technical point of view, two aspects should be considered: the possibility to use internally the wastes and the typology of both produced wastes and required inputs. From the waste producer point of view, only firms able to use internally wastes can implement the "internal exchange" model: for instance, if McDonald's did not use trucks, it could not internally use the biodiesel produced from fried oil but it should sell such a biodiesel on the external market, implementing in such a case the "external exchange" model. Moreover, from the waste user point of view, not all wastes can be used to generate new products but some wastes can only replace inputs. In these cases, the "co-product generation" model cannot be implemented.

From the economic point of view, firms can choose to implement the more profitable business model for themselves. For instance, McDonald's could sell the biodiesel from the fried oil on external markets, hence adopting the "internal exchange to co-product generation" scenario instead of the "internal exchange to input replacement" scenario. However, since it prefers to use biodiesel internally, such a use can be supposed more profitable. Moreover, the internal models may be more difficult to adopt for small firms because of the impossibility to share costs with partners.

Finally, from the strategic point of view, not all the business models have the same implementation risks. In this regard, for firms adopting the "internal exchange" model to exploit their wastes, the economic benefits stemming from the IS approach only depend on the firm's choices. Alternatively, for firms adopting the "external exchange" model to exploit their wastes, the economic benefits depend on the cooperation with other firms, and in particular on: i) the amount of wastes exchanged; ii) the cost-sharing policy negotiated. Both these issues are related to the cooperation barriers presented in Section 1.2. In fact, they are able to influence the willingness to cooperate of firms, which is fundamental for the development of symbiotic relationships among different firms. Moreover, the "co-product generation" model seems having high risks related to waste supply. Firms could be not willing to sustain high risks, preferring to adopt a less risky model.

Generally, the literature principally focused on the "external exchange to input replacement" scenario. In fact, theoretical definitions of IS refer to such a scenario. Furthermore, from the analyzed cases, such a scenario is the most implemented. Accordingly, communication platforms are focused on suggesting IS opportunities about the use of wastes in place of production inputs. In fact, the algorithms focus on identifying the technical correspondence among wastes and inputs. However, the "co-product generation" model has not been taken into account so far. Updating these algorithms in order to fill this gap may be useful in order to discover symbiotic opportunities so far unknown by firms, then further promoting the IS approach.

Table 2.9. Strengths and weaknesses for each business scenario at inter-firm level.

		Firm using wastes	
		Input replacement	**Co-products generation**
Firm producing wastes	**Internal exchange**	**Strengths** - no cooperation required - strategic independence - no transportation and transaction costs **Weaknesses** - limited symbiotic opportunities - additional costs cannot be shared	**Strengths** - no cooperation required - strategic independence - low waste supply risk - no transportation and transaction costs **Weaknesses** - limited symbiotic opportunities - additional costs cannot be shared - amount of new product depends on amount of wastes
	External exchange	**Strengths** - high symbiotic opportunities - additional costs can be shared **Weaknesses** - transportation and transaction costs arise - high level of cooperation required	**Strengths** - symbiotic opportunities among very different sectors - additional costs can be shared **Weaknesses** - transportation and transaction costs arise - amount of new product depends on amount of wastes - high level of cooperation required

Chapter 3. The role of contracts to support the emergence of self-organized industrial symbiosis networks

3.1 Introduction

An important barrier hampering the creation of IS relationships among different firms stems from the uneven distribution of the economic benefits created by the IS practice. When independent agents should cooperate to pursue a common goal (i.e., the formation of an ISN), but the benefits of cooperation are unevenly shared or cooperation is beneficial for some of them but detrimental for others, a misalignment incentive problem arises. A similar problem is found in supply chain management, where independent but interacting partnering firms (i.e., the supply network) should integrate operationally with each other, so as to pursue a common goal, i.e., the efficiency of the system as a whole. Total supply chain costs are indeed lower in the integrated supply chain than in a supply chain managed by independent efforts (Cachon, 2003; Tsay et al., 1999). It is widely recognized that firms are not prone to integrate with each other unless there is a central authority governing the entire system or strong social pressures. To push independent firms to pursue channel integration, proper supply contracts should be adopted (Cachon, 2003; Giannoccaro and Pontrandolfo, 2004; Tsay et al., 1999).

In this Chapter, I first investigated this issue by recognizing the existence of an incentive misalignment problem for the firms involved in cooperative symbiotic exchanges, which limits the formation of stable industrial symbiotic relationships, and then addressed the problem by designing a proper mechanism to handle it. In particular, I suggested designing contractual mechanisms ruling the relationship between the firms involved in the cooperative exchange, which modify the incentives of the individual firms, thus pushing each of them to behave in the desired way. In particular, I designed a contract aimed at: i) increasing the probability of establishing a stable ISN as a system level goal and ii) satisfying the *win–win* condition. This second condition is required to guarantee a spontaneous emergence of a symbiotic relationship. So doing, my study provides contributions to policy makers interested in implementing strategies and mechanisms to foster the formation of ISNs.

In approaching this problem, I framed ISNs as CASs (Chertow and Ehrenfeld, 2012). ISNs are viewed as networks of adaptive agents (firms) that emerge over time into coherent forms through interaction, without a central agent deliberately managing the system (Dooley, 1997; Holland, 2002, 1995). In doing so, ISNs are studied as an emergent process arising from the spontaneous decisions of independent but interconnected firms.

Agent-based simulation is an appropriate methodology to study CASs. It is well suited to studying the evolution of complex systems as an emergent phenomenon, resulting from bottom-up processes rather than being imposed by the modeler (Axelrod, 1997b; Epstein and Axtell, 1996; Gilbert and Troitzsch, 2005). The global properties of the ISN simply emerge from the spontaneous interactions of the decisions made by independent agents. The main goal of agent-based simulation is to enrich the understanding of certain fundamental processes (Axelrod, 1997b; Epstein and Axtell, 1996). Furthermore, it is a valuable tool for building new theories, concepts, and knowledge about some processes (Carley and Gasser, 1999).

The agent-based model, incorporating the main factors promoting and hampering the formation and the stability of the symbiotic relationship, is used to simulate the emergence of the ISN and to analyze the effect of the contract proposed on the formation of stable IS relationships in environments characterized by diverse levels of uncertainty and turbulence. Indeed, empirical observation shows that that one of the main factors that obstruct the diffusion of stable ISNs is the uncertainty and turbulence of the environment, which makes the resource flows available to establish the cooperative relationships unpredictable and the benefits arising from the IS difficult to assess. This in turn makes firms less prone to cooperate one with each other.

This Chapter is organized as follows. In Section 3.2, I discuss the theoretical background of this study. In particular, I review the main literature on IS, present the complex adaptive system approach to study the ISN, and describe the role of contracts and external environment in fostering and hampering the emergence of stable IS relationships. In Section 3.3, I describe the generic agent-based model of an ISN, the contract design, and the simulation analysis driven by empirical data concerning a real ISN made up by firms belonging to three different unrelated industries (sugar, alcohol, and fertilizer production). In Section 3.4, I discuss the results of the simulation analysis and I test the robustness of the proposed contract. Finally, conclusions are provided in Section 3.5.

3.2 Theoretical background

3.2.1 A complex adaptive systems approach to study industrial symbiosis networks

Framing ISNs as CASs means that they are the result of a self-organized process, where firms (agents) autonomously make the decision to establish symbiotic relationships among each other in the attempt to increase their "fitness", which corresponds to a performance dimension, without any overarching intention or deliberate planning by a central orchestrator, such as a leading firm or the government.

In framing ISNs as CASs, I identify the following elements: i) the firms with their specific attributes and goals (agents), ii) the networks among firms (interconnectedness), and iii) the path dependence (Table 3.1).

Each agent tends to increase an economic performance (fitness). One of the most important factors motivating firms to establish symbiotic relationships is, in fact, the economic benefit, stemming from the cost reduction in raw materials purchase and waste disposal, and from the additional revenues that can be gained selling wastes (Chertow and Ehrenfeld, 2012; Chertow and Lombardi, 2005; Esty and Porter, 1998; Jackson and Clift, 1998).

In CASs agents are heterogeneous. Firms interested in IS are characterized by idiosyncratic organizational factors affecting the decision to establish a symbiotic relationship, such as the desired return on investment, the size of capital invested and the payback time of the investment (Mirata, 2004). I assume that each firm is characterized by an individual propensity to establish the IS relationship, which specifies the extent to which the IS should be economically beneficial, (i.e., it should be large enough to cover the risk of the investment in the IS).

Table 3.1. Framing ISN as CAS.

Agent	Firm
Goal	To improve the fitness
Attributes	Desired return on investment Size of the investment
Interdependence networks	Material flows Social ties
Path dependence	High

Two types of networks characterize ISNs (Schiller et al., 2014). Firstly, a material flow network is recognizable made up by firms (nodes) connected to each other by means of resource exchange. The links in this type of network are mainly constrained by the technical features of the production process. Secondly, firms in ISN form a network of strong social ties, which create high social embeddedness (Boons and Howard-Grenville, 2009; Granovetter, 1985). There is a trust climate widespread in the industrial network, which is important for sustaining and nurturing the cooperative exchange (Gibbs, 2003; Gibbs and Deutz, 2007; Hewes and Lyons, 2008; Lambert and Boons, 2002). As stated in Section 1.1, trust is favored also by geographical proximity among firms, which enhances the transparency of actions and information sharing, and fosters cooperation among firms (Hewes and Lyons, 2008). The existence of strong social ties, familiarity, and shared norms among firms effectively cement the industrial symbiotic relationships and limit opportunistic behavior by firms. Therefore, even though the likelihood of achieving a unilateral and opportunistic gain in interrupting the symbiotic relationships is high, firms do not exploit this, because of the high level of trust (Jensen et al., 2011). Regarding this, recent studies have confirmed that many IS exchanges rely upon social relationships (Ashton, 2008; Jacobsen, 2006). Mirata (2004) and Lambert and Boons (2002) reported some cases where symbiotic linkages had been interrupted because of trust failure between firms. Thus, in framing ISNs as CASs I consider that firms are highly embedded with each other in the social context and that the existence of strong social ties influences the firms' behavior in improving their fitness.

A further property characterizing ISN dynamics is path dependence, which is one of the key features of a CAS whose evolution is governed by its own history (David, 1994). Path dependent is highly relevant in industrial ecology and to take it into account means to pay attention to the historical accumulations that have resulted from previous operations (Boons and Howard-Grenville, 2009).

3.2.2 The role of contracts for industrial symbiosis

The firms engaged in an ISN receive an economic benefit by exchanging resources. The volumes of by-products as well as the firms' production capacity and customer demand determines the amount of economic advantage associated with the industrial symbiosis and also how the benefits are shared among the parties involved.

It could happen that even in presence of high symbiotic advantage, the greatest part is gained by one firm, while the other receives a scant advantage, not significant enough to motivate it to sustain the cooperative exchange. In such a case, a misalignment incentive problem arises, which inhibits the creation of stable cooperative relationships. Therefore, to establish an effective IS relationship it is necessary that all parties achieve an economic benefit sufficient to cover the risk of the investment in the IS, but also that the benefit gained in case of industrial symbiotic exchange is higher than in absence of the cooperation (the so-called win-win condition). If this condition is satisfied the emergence of the industrial symbiotic relationship is high likely, since both parties have a benefit in forming the relationship. Therefore, this condition guarantees the spontaneous emergence of the symbiotic relationship as an independent choice of both parties involved.

A suitable mechanism to solve the misalignment incentive problem arising in the ISN is that of introducing contracts. In particular, I refer to a specific class, the supply contracts developed in supply chain management literature to rule the material flow relationships in supply chains so as to achieve system-wide efficiency (Govindan et al., 2013).

In fact, ISN and supply chains have a number of similarities. It is widely recognized in the literature that supply chain firms should integrate one with each other to pursue system-wide efficiency (channel coordination) (Bowersox et al., 1999; Christopher, 2011). Unless there is a central authority managing the supply chain as a whole, integration across multiple and independent firms is unlikely to occur, because pursuing a goal optimal for the system as a whole (system efficiency) may be locally detrimental for the single firm's performance. Thus, the single firms have scant incentive to integrate. Supply chain contracts push firms to collaborate one with each other in pursuing integration, in absence of a centralized authority governing the supply chain (Cachon, 2003).

Contracts utilize transfer mechanisms to align the interests of each independent firm to those of the whole system, so that even in case of autonomous decisions made by firms, the system efficiency is guaranteed (Giannoccaro and Pontrandolfo, 2004). Thanks to the alignment of the incentives, making a decision improving a local gain at the same time assures that the best decision for the system as a whole is taken.

Extensive reviews on the topic are available in the literature (Cachon, 2003; Govindan et al., 2013; Tang, 2006; Tsay et al., 1999). They propose classifications based on contractual schemes such as allocation of decision rights, pricing, minimum purchase commitments, quantity flexibility, buyback and return policies and the sources of risk.

The importance of contracts for IS is recognized in the literature (Chertow et al., 2004; Lombardi and Laybourn, 2006), but only a limited number of studies have rigorously addressed this issue. Examples of contractual clauses are those in which the firm using wastes pays a transfer price to the supplying firm or, on the contrary, the firm supplying wastes pays a transfer price to the receiving firm (Chertow et al., 2004; Lombardi and Laybourn, 2006).

To the best of my knowledge, very few studies have extended the logic of supply contracts to address the misalignment problem arising in ISNs. Contracts developed in the field of reverse logistics to coordinate the firms involved in the reuse of recycled materials and end-of-life products may address this issue (Sasikumar and Kannan, 2009, 2008a, 2008b). The incentive mechanisms used to coordinate the reverse logistics chain are quantity, time, quality, and price/deposit refund (Govindan et al., 2013).

I propose a simple transfer incentive mechanism based on price that is designed to pursue two main goals: i) to maximize the number of stable IS relationships (system goal), and ii) to assure the *win-win* condition. I discuss the design of the contract later in detail.

3.2.3 The importance of the external factors in industrial symbiosis

A dynamic external environment affects the emergence of a self-organized complex adaptive system, such as an ISN (Choi et al., 2001; Dooley, 1997). Empirical observation shows that it hinders the formation of industrial symbiotic relationships, above all, due to fluctuations in demand of the main products, supply availability, and market prices. Indeed, almost all cases of successful ISNs involve process industries characterized by scarce environmental dynamicity.

Environmental dynamicity is associated with both uncertainty and turbulence. Uncertainty deteriorates the economic and environmental performance of industrial symbiotic members (Lou et al., 2004), discouraging them from establishing long-term relationships. Uncertainty makes it difficult to assess the amount of resources available to IS so that quantifying the economic benefit arising from symbiosis becomes a hard task (Ehrenfeld and Gertler, 1997). In such conditions, firms are less motivated to share the economic benefits arising from IS and their propensity to establish cooperative relationships decreases.

Turbulence concerns the rate of environmental change. Fast changing environment requires firms to be flexible and to adapt quickly to the new external conditions (Reeves and Deimler, 2011). This requires the capacity of rapidly adding new partners as well as selecting new connections, thereby also changing the underlying pattern of interactions (Pathak et al., 2007). But since the symbiotic exchange is constrained by technical features and by the geographical proximity among firms, the number of new partners/connections could be limited, with a reduction in the firms' adaptive capability and a negative effect on performance.

While it is expected that the level of environmental dynamicity negatively affects the emergence of IS, the effect of environmental dynamicity on the relationship between the adoption of a contract and the emergence of a stable IS relationship is less intuitive. I explore the efficacy of contracts to foster the emergence of ISNs in scenarios characterized by different environmental dynamicity by means of agent-based simulation (Figure 3.1).

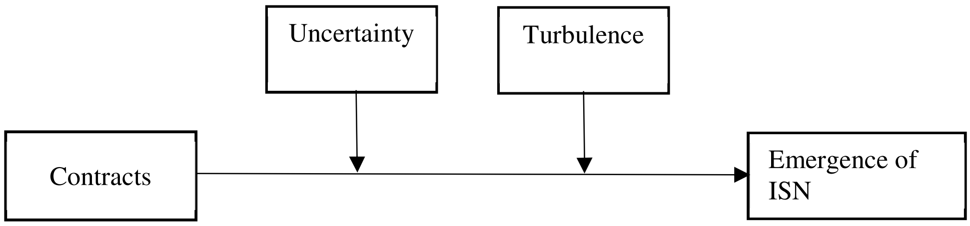


Figure 3.1. Conceptual framework

3.3 Methods

In this Section, I first present the agent-based simulation model of a generic ISN. I then describe how to design the contract aimed at fostering the emergence of stable industrial symbiosis relations. The model dynamics in different contexts characterized by the existence and the absence of the contract are also discussed. The last subparagraph presents the empirical data used to build the simulation models and the scenarios simulated to answer the research question.

3.3.1 The industrial symbiotic network model: Main features

I consider an industrial network as made up of N firms located into a geographic area. The firms belong to different unrelated industries, which are defined as production stages. Each stage is made up by a certain number of firms producing a single main product sold on the final market. The production requires a single raw material purchased from the external supply market and produces a single by-product destined to be disposed of in the landfill. Each firm is characterized by a stochastic final customer demand and pays raw material purchase and waste disposal costs.

Feasible symbiotic relationships exist that involve firms belonging to sequential stages as shown in Figure 3.2. For example, any firm belonging to the Stage B (j_B) can use as raw material the waste produced by any firm of the stage A (i_A) and can send its waste to any firm of the Stage C (k_C), which uses it as raw material. According to Chapter 2, I focused on the "external exchange to input replacement" scenario, since it is the most adopted one by firms involved in the IS practice.

Any firm is available to create symbiotic relationships. I assume that the symbiotic relationships are exclusive: a firm can send its waste only to one firm and can receive waste only from one firm. The industrial symbiotic network is thus characterized by a circular sequential pattern of links. Industrial complexes, such as integrated petrochemical complexes, sugar cane complexes, and pulp-and-paper mill complexes, are examples of sequential processes (Chertow, 2004).

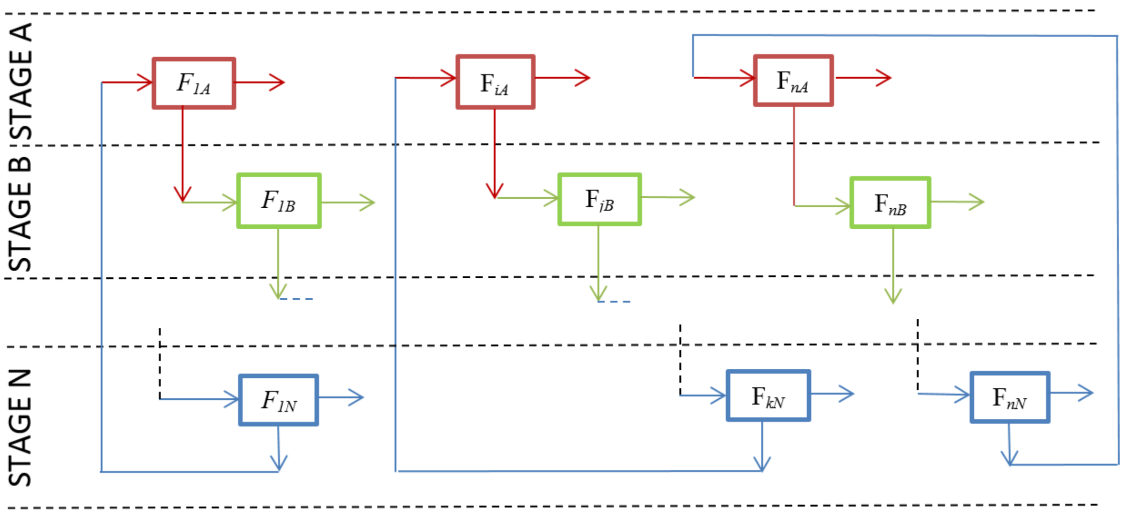


Figure 3.2. The network of symbiotic relationships.

The symbiotic relationships are modeled by the Enterprise Input-Output approach (see Chapter 2). The notation used, simplified rather than Chapter 2 for the sake of clarity, is reported in Table 3.2.

Table 3.2. Notation for EIO model

R_A, R_B, R_C	Units of raw materials to produce one unit of main product
W_A, W_B, W_C	Units of waste generated to produce one unit of main product
$x_{i_A}, x_{j_B}, x_{k_C}$	Final demand for the firms *i*, *j* and *k*
udc_i	Waste disposal cost paid by firm *i*
upc_i	Purchase cost of the raw material paid by firm *i*

Under the hypothesis that one by-product unit perfectly replaces one raw material unit (s=1), the waste quantity sent from a generic firm i_A to a generic firm j_B at time t is given as follows:

$$e_{i_A \to j_B}(t) = \min\{W_A \cdot x_{i_A}(t); R_B \cdot x_{j_B}(t)\} \tag{3.1}$$

3.3.2 The agent-based model of the industrial symbiotic network

Each firm *i* in a stage of the industrial network is modeled as an agent, who decides to establish a symbiotic relationship with a firm *j* belonging to the feasible symbiotic stage. For example, if firm *i* belongs to stage A, it should decide to establish a symbiotic relationship with a firm *j* belonging to B.

A fitness function $F_{i \to j}$ ($F_{j \to i}$) is defined that measures the extent to which it is beneficial for the firm *i* (*j*) to establish a symbiotic relationship with firm *j* (*i*). The higher the fitness value, the higher the willingness of the agent to establish/maintain the symbiotic relationship.

In particular, I assume that the agent *i* decides to establish the symbiotic relationship with *j*, only if the fitness value associated with the symbiotic relationship exceeds a given threshold ($F_{i\rightarrow j}$>T_i). This means that a symbiotic relationship between *i* and *j* is established only if both the agents *i* and *j* have a fitness higher than the threshold. The threshold models the firms' propensity to implement the symbiotic relationships. This propensity depends on the idiosyncratic attributes of the firms discussed above, such as the desired return on investment (Mirata, 2004) or the size of the investment needed to modify/buy production facilities for using the waste in the production process (Chertow, 2004; Esty and Porter, 1998; Jacobsen, 2006).

The fitness function is defined as the firm's economic performance. The economic advantage $EB_{i\rightarrow j}$ ($EB_{j\rightarrow i}$) for firm *i* (*j*) to establish a symbiotic relationship with firm *j* (*i*) is computed as the ratio between the symbiotic advantage $SA_{i\rightarrow j}$ ($SA_{j\rightarrow i}$), i.e., the economic advantage due to symbiotic relationship and the costs of raw material purchase and waste disposal in absence of symbiosis C_i (C_j).

As said above, path dependence is an important feature of a CAS-based self-organized ISN. I include it assuming that the longer the time the firms are involved in an effective resource exchange, the lower the importance of the economic benefit at time *t* to motivate them to decide to maintain (or not) the symbiotic relationship (Chertow, 2007). Therefore, the fitness function of the firm *i* to establish a symbiotic relationship with firm *j* at the time period *t* is defined as follows:

$$F_{i\rightarrow j}(t) = \frac{1}{L_{ij}(t)} \cdot EB_{i\rightarrow j}(t) + \left[1 - \frac{1}{L_{ij}(t)}\right] \cdot EB_{i\rightarrow j}(t-1) \tag{3.2}$$

with $L_{ij}(t)$ indicating the time length of the IS relationship between firms *i* and *j* at time *t*.

Social embeddedness and trust are further important properties of a self-organized ISN. The level of trust is modeled as the probability of each firm making decisions that are not detrimental to the other party. This goodwill trust is due to social strong ties. In my model thus the level of trust influences the behavior of firms that are linked in a mutual beneficial symbiotic relationship. In such a case, one of both parties could decide to interrupt the relationship, because of the opportunity to establish more beneficial relationships. In fact, even when the relationship is beneficial one of the parties could always search for a different symbiotic partner with whom the benefit coming from the symbiosis could be improved. The higher the probability that the firms maintain mutual beneficial relationship, the higher the level of trust in the relationship. Thus, I define TRUST as the probability of maintaining the relationship, while (1- TRUST) is the probability of seeking a new partner.

Moreover, I consider that the symbiotic exchange between two generic firms may be ruled by three different contractual options. The first case corresponds to the scenario in which firms do not adopt any contract: wastes are transferred between companies without any fee paid. Therefore, no share of symbiotic benefits occurs among the firms involved: the firm producing waste gains benefits due to the reduction of waste disposal cost, whereas the firm receiving waste gains from lower raw materials purchase cost.

The second case concerns a contractual mechanism in which firm *j* pays firm *i* to receive its waste. The price paid by *j* can be expressed as follows:

$$pc_j^{symb} = \beta_{ij} \cdot pc_j \quad \text{with } 0 < \beta_{ij} < 1 \tag{3.3}$$

where β_{ij} denotes the fee (in percentage of raw material purchase cost) paid by firm *j* to firm *i* to purchase waste from it. In such a case, the symbiotic benefit due to the cost reduction of raw material purchase is shared between the two firms, where β_{ij} is the quota gained by the firm *i*.

The third case refers to a contractual mechanism where firm *i* pays firm *j* to supply it its waste. The price paid by *i* can be expressed as follows:

$$dc_i^{symb} = \alpha_{ij} \cdot dc_i \text{ with } 0 < \alpha_{ij} < 1 \tag{3.4}$$

where α_{ij} denotes the fee (in percentage of waste disposal cost) paid by firm *i* to firm *j* to supply it its waste. In such a case, the contract parameter α_{ij} rules how the benefit due to the reduction in waste disposal cost is shared between the two firms. The higher α_{ij}, the higher the quota of the symbiotic benefit firm *j* gains. The quota of the symbiotic benefit of firm *i* is $1 - \alpha_{ij}$.

The graphical representation of the monetary flows at the time *t* between two firms involved in an industrial symbiosis relationship is given in Figure 3.3.

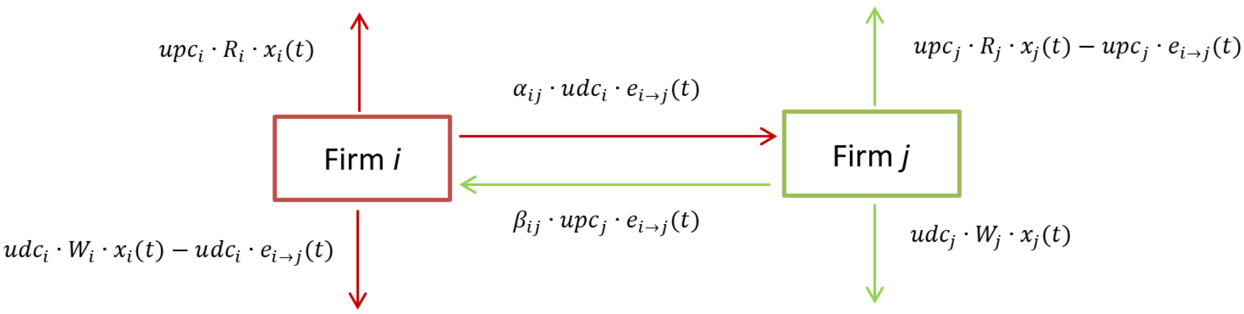


Figure 3.3. Monetary flows in case of industrial symbiosis.

Table 3.3 summarizes the three contractual cases examined, showing the value of the symbiotic benefits gained by firms *i* and *j*.

Table 3.3. The contractual options.

Contractual setting	Contract parameters	Symbiotic benefits
Absence of contract	$\alpha_{AB} = 0, \beta_{AB} = 0$	$SA_{i\to j}(t) = udc_i \cdot e_{i_A\to j_B}(t)$ $SA_{j\to i}(t) = upc_j \cdot e_{i_A\to j_B}(t)$
Firm pays to supply its waste	$\alpha_{AB} > 0, \beta_{AB} = 0$	$SA_{i\to j}(t) = (1-\alpha_{AB}) \cdot udc_i \cdot e_{i_A\to j_B}(t)$ $SA_{j\to i}(t) = (\alpha_{AB} \cdot udc_i + upc_j) \cdot e_{i_A\to j_B}(t)$
Firm pays to purchase by-products	$\alpha_{AB} = 0, \beta_{AB} > 0$	$SA_{i\to j}(t) = (dc_i + \beta_{AB} \cdot upc_j) \cdot e_{i_A\to j_B}(t)$ $SA_{j\to i}(t) = (1-\beta_{AB}) \cdot upc_j \cdot e_{i_A\to j_B}(t)$

Considering a generic contract ruling the symbiotic relationship between the firms of two generic symbiotic stages, the economic benefit of the symbiotic relationship for the firms *i* and *j* at time *t* are defined as:

$$EB_{i\to j}(t) = \frac{SA_{i\to j}(t)}{C_{i_A}(t)} = \frac{\left[(1-\alpha_{AB}) \cdot udc_i + \beta_{AB} \cdot upc_j\right] \cdot e_{i_A\to j_B}(t)}{(upc_i \cdot R_A + udc_i \cdot W_A) \cdot x_{i_A}(t)} \tag{3.5}$$

$$EB_{j\to i}(t) = \frac{SA_{j\to i}(t)}{C_{j_B}(t)} = \frac{\left[\alpha_{AB} \cdot udc_i + (1-\beta_{AB}) \cdot upc_j\right] \cdot e_{i_A\to j_B}(t)}{(upc_j \cdot R_B + udc_j \cdot W_B) \cdot x_{i_B}(t)} \tag{3.6}$$

3.3.3 The contract design

My aim is to identify the optimal value of the contract parameters α_{ij} and β_{ij}, ruling a generic symbiotic relationship, with the aim of increasing the formation of a stable relationship and satisfying the win-win condition.

The first aim is pursued by minimizing the probability that the symbiotic relationship does not occur or is broken (failure). In particular, this happens under each of four conditions: 1) when the relationship is not economically convenient for firm *i* ($F_{i\to j} < T_i$) even though it is convenient for firm *j* ($F_{j\to i} \geq T_j$); 2) when the relationship is beneficial for firm *i* ($F_{i\to j} \geq T_i$) but not for firm *j* ($F_{j\to i} < T_j$); 3) when the relationship is not economically convenient for both the firms ($F_{i\to j} < T_i$ and $F_{j\to i} < T_j$); 4) when the relationship is convenient for both firms involved ($F_{i\to j} \geq T_i$ and $F_{j\to i} \geq T_j$) but fails for lack of mutual trust.

Since the final demand is a stochastic variable, I compute the probability of each of the four events as follows:

$$p_1 = P(F_{i\to j} < T_i) \cdot \left[1 - P\left(F_{j\to i} < T_j\right)\right]$$
$$p_2 = \left[1 - P(F_{i\to j} < T_i)\right] \cdot P\left(F_{j\to i} < T_j\right)$$

$$p_3 = P(F_{i\to j} < T_i) \cdot P\big(F_{j\to i} < T_j\big)$$

$$p_4 = \big[1 - P(F_{i\to j} < T_i)\big] \cdot \big[1 - P\big(F_{j\to i} < T_j\big)\big] \cdot (1 - \mathrm{TRUST})^2$$

Thus, I set a non-linear programming minimization problem choosing as objective function the probability of failure of the relationship.

$$\mathrm{Min}\, p_f = p_1 + p_2 + p_3 + p_4$$

subject to the following constraints:

$$\begin{cases} 0 \le \alpha_{ij} < 1 \\ 0 \le \beta_{ij} < 1 \\ \overline{EB}_{i\to j}{}^{C} \ge \overline{EB}_{i\to j}{}^{NC} \\ \overline{EB}_{j\to i}{}^{C} \ge \overline{EB}_{j\to i}{}^{NC} \end{cases}$$

where $\overline{EB}_{i\to j}{}^{C}$ and $\overline{EB}_{i\to j}{}^{NC}$ are the expected value of the economic benefits gained by the firms *i* (*j*) in presence of the contract and in absence of the contract, respectively. The last two constraints guarantee the *win-win* condition. The expected value of the economic benefits gained by the firms *i* and *j* involved in the symbiotic relationship are thus computed as follows:

$$\overline{EB}_{i\to j} = (1 - p_f) \cdot \frac{\big[(1-\alpha_{ij}) \cdot udc_i + \beta_{ij} \cdot upc_j\big] \cdot \min\big\{W_i \cdot \bar{x}_i; R_j \cdot \bar{x}_j\big\}}{(upc_i \cdot R_i + udc_i \cdot W_i) \cdot \bar{x}_i} \tag{3.7}$$

$$EB_{j\to i} = (1 - p_f) \cdot \frac{\big[\alpha_{ij} \cdot udc_i + (1-\beta_{ij}) \cdot upc_j\big] \cdot \min\big\{W_i \cdot \bar{x}_i; R_j \cdot \bar{x}_j\big\}}{(upc_j \cdot R_j + udc_j \cdot W_j) \cdot \bar{x}_j} \tag{3.8}$$

3.3.4 The agent-based model dynamics

The agents of my model are the firms. They accomplish the following actions to improve their economic benefit:

- seeking a firm with which to establish a symbiotic relationship;
- measuring the fitness of the relationship;
- interrupting an industrial symbiotic relationship;
- establishing an industrial symbiotic relationship.

At each time period *t,* firm *i* decides to seek a firm with which to connect, or not. In particular, the firm searches for a firm with which to establish a symbiotic relationship either when it is not connected with any firm (free) or when it is connected with firm *j*, depending on different conditions. First, firm *i* computes the fitness value of the relationship with *j* using Equation 3.2. If the fitness value for *i* or *j* is lower than the threshold value, the link *i-j* is interrupted and firm *i* searches for another firm with which to connect. If both the fitness values for *i* and *j* are greater that the threshold value, only with a given probability *p* (*p=TRUST*) the relationship is maintained, but with probability 1-*TRUST* firm *i* seeks another available firm *k*, belonging to the same feasible symbiotic stage, with which to connect to improve its economic advantage over time.

Let us suppose that firm *k* is chosen, the fitness $F_{i \to k}$ is computed: if $F_{i \to k} > F_{i \to j}$, firm *i* finds its interest lies in interrupting its actual link with firm *j* and linking with firm *k*. The emergence of the new relationship *i-k* depends now on firm *k*. It may be free, i.e., not involved in a symbiotic relationship with another firm, or conversely it may be linked with another firm. If *k* is free, the link *i-k* is established only if the relationship is economically convenient for *k* ($F_{k \to i} \geq T_k$). If firm *k* is not free but linked with firm *q*, then firm *k* evaluates whether to interrupt its current relationship with probability p=1-*TRUST*. The new relationship *i-k* arises if the new link is more economically convenient for *k* than the previous one, i.e., $F_{k \to i} > F_{k \to q}$.

When firm *i* is not connected with any firm, the relationship with firm *k* is established only if the fitness value for *i* is above the threshold ($F_{i \to k} \geq T_i$).

Figure 3.4 shows the flow chart describing the agent decision-making process.

For each time period, the number of existing symbiotic relationships is computed. The process is repeated for a given number of time periods (simulation time) and the number of symbiotic relationships at the end of simulation is measured. A high number of symbiosis relationships compared with the total number of feasible symbiotic relationships at the end of the simulation means that an ISN has successfully emerged.

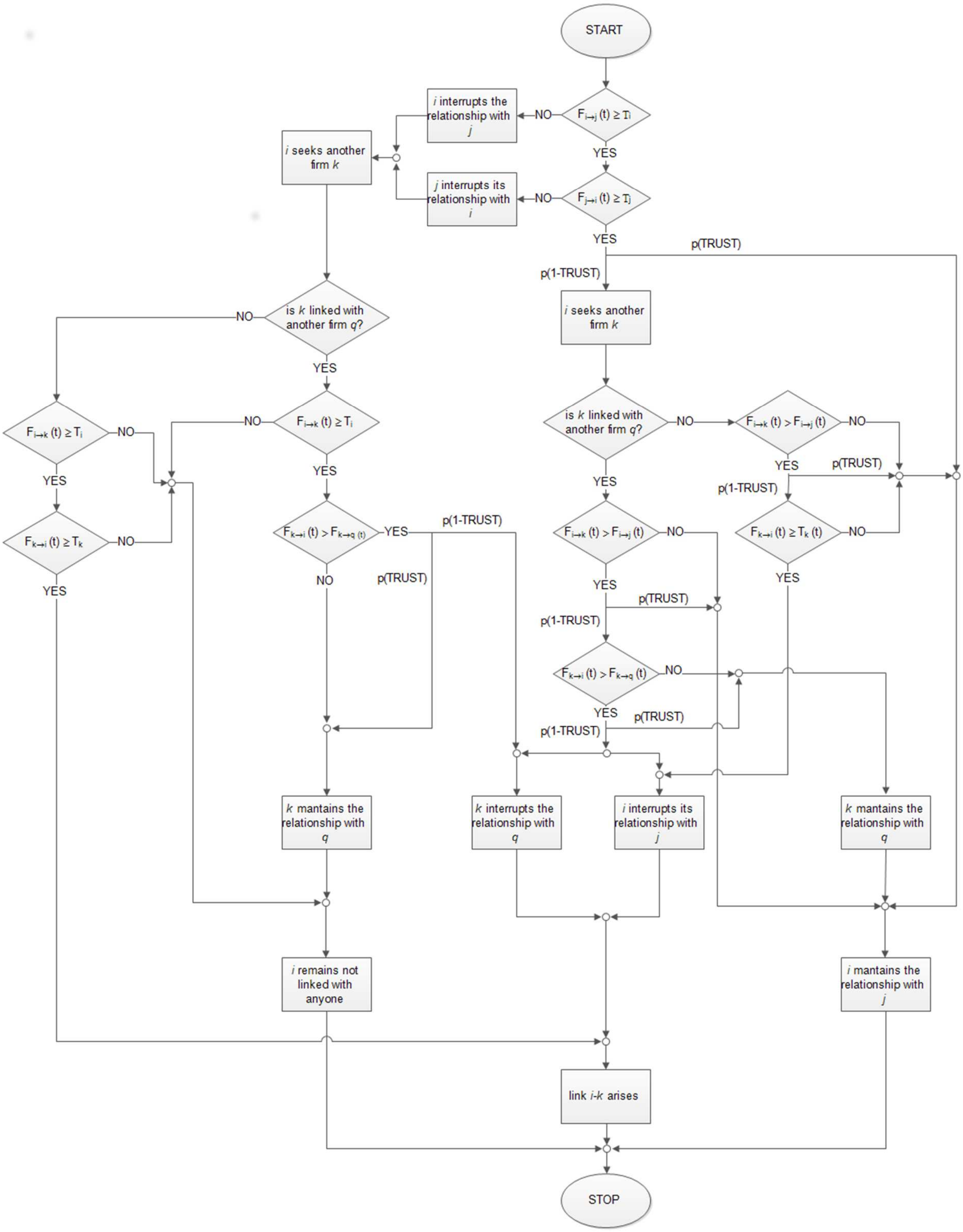


Figure 3.4. Flow chart of the agent decision-making process.

3.3.5 Simulation analysis driven by empirical data

The agent-based model above was used to carry out a simulation analysis to investigate the emergence of stable symbiotic relationships in a business network, defined using data driven by an empirical case. In particular, I simulated and measured the emergence of an ISN in scenarios characterized by increasing environmental dynamicity and trust level, in two diverse settings, one defined by the absence of contract ruling the symbiotic exchange (*baseline model*) and the other where the proposed contractual mechanism is adopted by firms involved in the symbiotic relationship (*contract*). So doing, I analyzed the effectiveness of the contractual mechanisms to foster the emergence of IS in diverse environments, as proposed in my research question.

3.3.5.1 Case-study data

To build my simulation model I used data referring to a real case study concerning a three-stage ISN discussed in Yang and Feng (2008) and Zhu et al. (2007). Stage A includes firms that produce sugar as their main product. To produce it, those firms require fertilizers and generate molasses as a by-product. Stage B is made up by firms producing alcohol. They can use molasses as raw material and in turn generate alcohol slops; this waste can be used in the fertilizer production process (stage C). Finally, the waste produced by the third process can be sent to the firms in stage A and used in sugarcane plantations (Figure 3.5).

Each firm observed a stochastic final customer demand over time, distributed according to a normal distribution with a given mean and variance. At the beginning of the simulation, the symbiotic relationships among firms were generated at random: each firm of a stage being linked with a firm of the feasible symbiotic stage. Since I modeled a symbiotic network characterized by a sequential pattern, each firm was able to establish just two relationships: one with a firm in the downstream stage and one with a firm in the upstream stage.

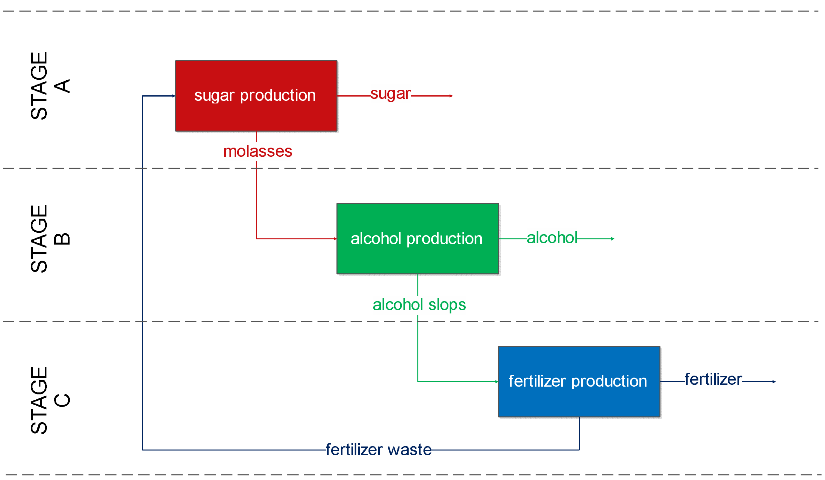


Figure 3.5. The model of the feasible industrial symbiotic relationships.

Numerical data on the main product demand, the raw material requirements, and the waste produced are shown in Table 3.4. The values of the technical coefficients for the three stages are obtained from secondary data and shown in Table 3.5. Purchase costs of the fertilizer, the molasses and the alcohol slops are 4.000 $/t, 800 $/t, and 70$/t, respectively; disposal cost is 90 $ per ton (supposed equal for all types of waste).

Table 3.4. Numerical data (ton per year).

Main product demand		Raw material requirement		Waste	
Sugar	450.000 t/y	Fertilizer	19.800 t/y	Molasses	99.000 t/y
Alcohol	25.000 t/y	Molasses	100.000 t/y	Alcohol slops	20.000 t/y
Fertilizer	30.000 t/y	Alcohol slops	12.000 t/y	Fertilizer waste	3.000 t/y

Table 3.5. Values of the technical coefficients.

Stage	*R*	*W*
A	$0.044\ \dfrac{t\ fertilizer}{t\ sugar}$	$0.2\ \dfrac{t\ molasses}{t\ sugar}$
B	$4\ \dfrac{t\ molasses}{t\ alcohol}$	$0.8\ \dfrac{t\ alcohol\ slops}{t\ alcohol}$
C	$0.4\ \dfrac{t\ alcohol\ slops}{t\ fertilizer}$	$0.1\ \dfrac{t\ waste\ fertilizer}{t\ fertilizer}$

3.3.5.2 Simulation scenarios

The simulation scenarios were defined by varying both the levels of environmental uncertainty and turbulence and by considering four different levels of trust.

The environmental uncertainty was modeled through the variability in the main product demand of the firm (final customer demand). The value of the final customer demand of each firm at each time period *t* was drawn at random from a normal distribution of μ mean and σ standard deviation. Thus, σ controlled the environmental uncertainty: the higher the standard deviation, the higher the uncertainty.

Environmental turbulence concerns the rate of change and was modeled by means of the number of time periods (Δ) in which the final customer demand of the firm was kept constant over time. The higher the number of time periods in which the demand was kept constant, the more static the environment. Four σ/μ values and two Δ values were considered.

To control the results for the effect of trust, I considered four trust levels, where the highest level of trust was characterized by TRUST=1 and the lowest level by TRUST=0.25.

Summarizing, the simulation plan consisted of thirty-two scenarios, resulting from the eight cases defined by varying the environmental dynamicity in the four considered cases of different trust. Table 3.6 summarizes the values of all parameters used to define the simulation scenarios. In each scenario, I assumed that each stage was made up of 50 firms, differing from each other by the value of the final customer demand at time period *t*. The threshold value for all firms in all stages was set equal to 0.1.

Table 3.6. Parameters of the simulation scenarios.

Variable	Modeling variable	Values
Environmental uncertainty	Standard deviation of main product demand	σ/μ = 0.1, 0.2, 0.3, 0.4
Environmental turbulence	Number Δ of time periods the main product demand is fixed	Δ = 1, 5
Trust level	Probability of the firms (TRUST) to make decisions not detrimental for the other party	TRUST=1, 0.75, 0.50, 0.25

3.4 Results

I simulated each scenario for a simulation run of 1000 periods and replicate 100 times so as to give statistical significance results. The final number of total symbiotic relationships was computed at the end of the simulation time and averaged across the replications.

3.4.1 The baseline model

In Table 3.7 the simulation results of the baseline model are shown (the standard deviation of the average number of the symbiotic relationships is given in brackets). The scenario characterized by low environmental uncertainty and low turbulence shows the highest number of symbiotic relationships, as expected. With fixed turbulence, as the environmental uncertainty increases moving from low to high, the average number of relationships decreases. For example, in the case of high trust (TRUST = 1) and low turbulence, the number of stable industrial symbiosis relationships decreases from 117.57 to 99.93, as the uncertainty rises. Moreover, the negative effect of uncertainty is greater for scenarios characterized by high turbulence. In fact, for example in the case of TRUST = 1 the decrease in the average number of symbiotic relationship is on average 5.2% for low turbulence and 10.3% for high turbulence. With fixed uncertainty, as environmental turbulence rises, the average number of relationships declines and the negative effect of the turbulence grows with increasing uncertainty. For example, in the case of TRUST = 1, the decrease is about 22.5% for low uncertainty and 34.6% for high uncertainty.

Trust positively affects the number of stable symbiotic relationships, as expected. It has a higher impact in scenarios characterized by low uncertainty and low turbulence. In fact, comparing the results in case of TRUST = 1 and TRUST = 0.25 the increase in the number of symbiotic relationships provided by trust is on average 22.5% in case of low turbulence and 19.95% in case of high turbulence, while it is on average 28.9% and 18.6% in the case of low and high uncertainty, respectively.

These results validate my simulation model, which indeed is able to reproduce the empirical observations and the dynamics identified in the literature.

Table 3.7. Average number of symbiotic relationships at the end of simulation time.

	TRUST=1			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	117.57 *(3.56)*	105.51 *(3.98)*	101.50 *(4.37)*	99.93 *(4.64)*
High T (Δ=1)	91.17 *(4.51)*	74.37 *(5.04)*	68.51 *(5.54)*	65.40 *(5.50)*

	TRUST =0.75			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	110.56 *(3.65)*	102.23 *(3.70)*	99.07 *(4.54)*	96.18 *(5.28)*
High T (Δ=1)	85.47 *(4.65)*	70.88 *(5.31)*	66.83 *(5.13)*	61.51 *(5.40)*

	TRUST =0.50			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	100.88 *(3.92)*	94.63 *(4.88)*	91.27 *(4.15)*	90.04 *(4.78)*
High T (Δ=1)	78.19 *(4.23)*	67.37 *(5.07)*	62.68 *(5.17)*	60.42 *(4.76)*

	TRUST =0.25			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	92.28 *(3.65)*	86.58 *(4.10)*	84.69 *(4.05)*	82.70 *(4.54)*
High T (Δ=1)	69.89 *(3.98)*	62.99 *(4.72)*	59.67 *(5.10)*	56.16 *(6.41)*

U = Uncertainty; T=Turbulence (mean and standard deviation of the final number of symbiotic relations)

3.4.2 The contract case

In this section, I consider the case in which the symbiotic relationships are ruled by the proposed contract.

I first designed the contract using the minimization problem presented in Section 3.3.3. It was applied to rule each type of IS relationships (A-B, B-C, and C-A) and in the simulation scenario resulting from the combination of the different levels of uncertainty and trust. Notice that the optimal contractual parameters α and β are in fact different in each scenario.

Table 3.8 shows in the first column the probability of failure for each type of symbiotic relationship (A-B, B-C, A-C). The second and third columns present the optimal values of the contract parameters α_{ij} and β_{ij}, and the fourth column the new probability of failure.

Notice that the minimization problem applied to stage C-A has no solution that satisfies all the constraints of the problem, thus α=β=0. For the stages A-B and B-C α and β are greater than zero in all the scenarios. This means that firm producing waste should pay the receiving firm to send its waste and at the same time the firm receiving waste should pay the firm producing waste to purchase it. The real economic flow between firms is equal to $(\alpha_{ij} \cdot dc_i - \beta_{ij} \cdot pc_j) \cdot \min\{W_i \cdot \bar{x}_i; R_j \cdot \bar{x}_j\}$. The sign gives the flow direction: if this quantity is higher than zero, money flows from firm producing waste to firm receiving waste. Conversely, the economic flow is from the firm receiving waste to the firm producing waste.

Table 3.8. Results in the contractual setting.

TRUST=1

		No contractual mechanism	With contractual mechanism		
		pf	**α**	**β**	**pf**
A-B	**σ/μ=0.1**	44%	0.2466	0.7126	0.81%
	σ/μ=0.2	47%	0.2880	0.7094	13.70%
	σ/μ=0.3	48.1%	0.2381	0.5280	29.84%
	σ/μ=0.4	49.2%	0.2386	0.3832	42.66%
B-C	**σ/μ=0.1**	24.6%	0.3407	0.6538	3.91%
	σ/μ=0.2	32.8%	0.2411	0.5747	8.54%
	σ/μ=0.3	37.5%	0.3211	0.6606	16.97%
	σ/μ=0.4	40.9%	0.2610	0.5172	27.82%

TRUST = 0.75

		No contractual mechanisms	With contractual mechanism		
		pf	**α**	**β**	**pf**
A-B	**σ/μ=0.1**	47.5%	0.2385	0.7041	7.0%
	σ/μ=0.2	50.3%	0.3377	0.7662	19.1%
	σ/μ=0.3	51.3%	0.6026	0.9381	47.4%
	σ/μ=0.4	52.4%	0.7001	0.9025	46.2%
B-C	**σ/μ=0.1**	29.4%	0.1763	0.4424	9.9%
	σ/μ=0.2	37.0%	0.2578	0.5962	14.3%
	σ/μ=0.3	41.4%	0.3869	0.7452	22.2%
	σ/μ=0.4	44.6%	0.4746	0.7917	32.3%

TRUST = 0.50

		No contractual mechanism	With contractual mechanism		
		pf	**α**	**β**	**pf**
A-B	**σ/μ=0.1**	58.0%	0.3662	0.8478	25.6%
	σ/μ=0.2	60.3%	0.4360	0.8767	35.2%
	σ/μ=0.3	61.1%	0.4835	0.8040	47.4%
	σ/μ=0.4	61.9%	0.3543	0.5134	57.0%
B-C	**σ/μ=0.1**	43.5%	0.0627	0.2964	27.9%
	σ/μ=0.2	49.6%	0.5083	0.9182	31.4%
	σ/μ=0.3	53.2%	0.4139	0.7799	37.7%
	σ/μ=0.4	55.7%	0.5156	0.8444	45.9%

Table 3.8. Results in the contractual setting (continued from previous page).

TRUST = 0.25

		No contractual mechanism	With contractual mechanism		
		pf	**α**	**β**	**pf**
A-B	**σ/μ=0.1**	75.5%	0.0894	0.5364	56.6%
	σ/μ=0.2	76.8%	0.5215	0.9729	62.2%
	σ/μ=0.3	77.3%	0.4706	0.7896	69.3%
	σ/μ=0.4	77.8%	0.2946	0.4462	74.9%
B-C	**σ/μ=0.1**	67.0%	0.3403	0.6532	58.0%
	σ/μ=0.2	70.6%	0.1948	0.5151	60.0%
	σ/μ=0.3	72.7%	0.3478	0.6949	63.7%
	σ/μ=0.4	74.2%	0.2898	0.5542	68.4%

I ran the simulation in the same scenarios as those of the baseline setting. The simulation results are shown in Table 3.9. They confirm the trends observed in the baseline model: the average number of symbiotic relationships decreases as both the uncertainty and the turbulence rise. Moreover, the decrease is greater in the case of high turbulence and high uncertainty. Trust fosters the emergence of stable symbiotic relationships, in particular when both uncertainty and turbulence are low. Comparing the result in the case of low trust (TRUST = 0.25) and high trust (TRUST = 1), on average the number of stable relationships increases by about 27% and 23% in the case of low and high turbulence, respectively. Compared to the baseline setting, the positive effect of trust is greater when the contract is used.

Table 3.9. Average number of symbiotic relationships in presence of contractual settings.

	TRUST=1			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	141.85 *(2.06)*	125.65 *(3.36)*	114.67 *(4.14)*	103.33 *(4.54)*
High T (Δ=1)	130.69 *(3.54)*	97.79 *(4.79)*	81.55 *(5.88)*	72.27 *(5.20)*

	TRUST=0.75			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	129.76 *(3.13)*	120.05 *(3.59)*	109.34 *(4.57)*	101.62 *(4.43)*
High T (Δ=1)	121.26 *(3.71)*	94.13 *(5.61)*	78.75 *(4.69)*	66.85 *(5.31)*

	TRUST=0.50			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	116.34 *(3.52)*	108.61 *(3.48)*	100.76 *(3.82)*	93.47 *(4.68)*
High T (Δ=1)	109.08 *(4.05)*	87.96 *(4.19)*	73.91 *(6.05)*	66.16 *(5.54)*

	TRUST=0.25			
	Low U (σ/μ=0.1)	Low-Medium U (σ/μ=0.2)	Medium-High U (σ/μ=0.3)	High U (σ/μ=0.4)
Low T (Δ=5)	105.27 *(3.83)*	100.05 *(4.37)*	93.68 *(3.93)*	82.47 *(4.90)*
High T (Δ=1)	96.82 *(3.53)*	80.41 *(4.77)*	69.36 *(4.59)*	61.61 *(4.98)*

U = Uncertainty; T=Turbulence (mean and standard deviation of the final number of symbiotic relations)

I compared the results achieved in the contract and baseline settings (Table 3.10). Notice that the use of the contract determines an increase in the number of symbiotic relationships in all the scenarios considered. On average, the number of symbiotic relationships increases by about 12% and 25% in case of low and high turbulence, respectively, while the rise drops from 29% to 6% moving from low to high uncertainty. The highest benefit is thus achieved in the case of low uncertainty and high turbulence.

The effect of contracts is greater for higher levels of trust, *ceteris paribus*. The higher the level of trust there is, the greater the increase in the number of industrial symbiosis relationships. In the case of high trust (TRUST=1), the increase in the number of industrial symbiosis relationships ranges from a minimum value of 3% (in the case of high uncertainty and low turbulence) to a maximum value of 43% (in the case of low uncertainty and high turbulence). The proposed contract is thus particularly beneficial to foster the emergence of ISN in case of high trust, low uncertainty, and high turbulence (Table 3.11).

Table 3.10. Comparison between the baseline and the contract settings (percentage of IS relationships on the total).

		TRUST=1			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	94.56%	83.76%	76.45%	68.89%
	NC	78.38%	70.34%	67.67%	66.62%
High T	C	87.13%	65.19%	54.37%	48.18%
	NC	60.78%	49.58%	45.67%	43.60%

		TRUST=0.75			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	86.51%	80.03%	72.89%	67.74%
	NC	73.70%	68.16%	66.04%	64.12%
High T	C	80.84%	62.75%	52.50%	44.56%
	NC	56.98%	47.25%	44.56%	41.01%

		TRUST=0.50			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	77.56%	72.41%	67.18%	62.31%
	NC	67.25%	63.09%	60.84%	60.03%
High T	C	72.72%	58.64%	49.27%	44.11%
	NC	52.13%	44.91%	41.79%	40.28%

		TRUST=0.25			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	70.18%	66.70%	62.45%	54.98%
	NC	61.52%	57.72%	56.46%	55.13%
High T	C	64.55%	53.61%	46.24%	41.07%
	NC	46.59%	41.99%	39.78%	37.44%

U = Uncertainty; T=Turbulence; C= Presence of Contract; NC=Absence of Contract

Table 3.11. Percentage of the increase in the number of stable industrial symbiosis relationships.

	Low U	Low-Medium U	Medium-High U	High U	*Mean*
Trust =1					
Low T	21%	19%	13%	3%	*14%*
High T	43%	31%	19%	11%	*26%*
Trust=0.75					
Low T	17%	17%	10%	6%	*13%*
High T	42%	33%	18%	9%	*25%*
Trust=0.50					
Low T	15%	15%	10%	4%	*11%*
High T	39%	31%	18%	10%	*24%*
Trust=0.25					
Low T	14%	16%	11%	0%	*10%*
High T	39%	28%	16%	10%	*23%*
Mean	*29%*	*24%*	*14%*	*6%*	

3.4.3 Model robustness

I tested the robustness of the results simulating a more complex ISN introducing a fourth stage concerning the pulp production. This more complex ISN is composed of the following stages: the stage A made by firms involved in the sugar production, which produce bagasse as waste and require waste fertilizer as raw materials; the stage B which involves firms producing pulp as main product, generating bleaching water as by-product, and using bagasse as raw materials; the stage C including firms producing alcohol slops as waste and using bleaching water in the alcohol production; stage D (fertilizer production) made up by firms producing fertilizer waste and requiring alcohol slops (Figure 3.6).

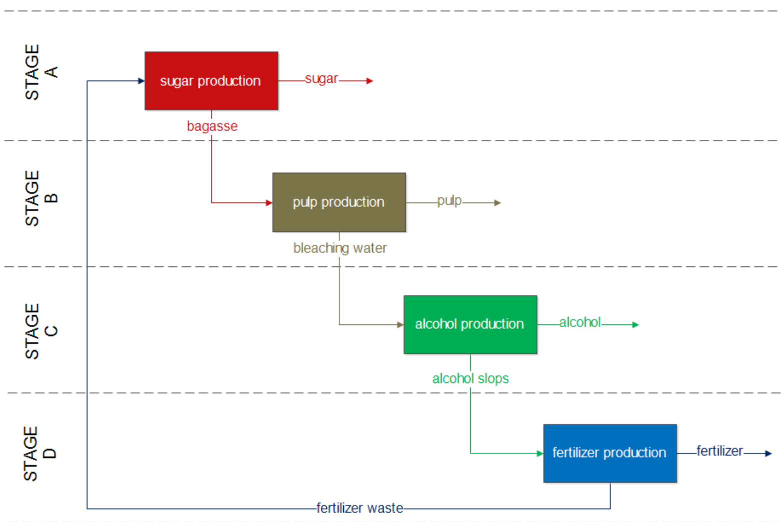


Figure 3.6. The model of the feasible industrial symbiotic relationships in the more complex ISN.

I ran simulations in both the baseline and contract cases for all the scenarios considered and collect results. The outcomes revealed the same patterns confirming that even in the case of a more complex network the effect of the contractual mechanism is to increase the number of stable IS relationships. Similarly, results showed that the highest benefits are achieved for low uncertainty and high turbulence of the external environment.

Data concerning the main product demand, the raw materials requirements, and the waste produced by the firms in the four production stages are shown in Table 3.12. The values of the technical coefficients for the four stages are provided in Table 3.13. Purchase costs of the fertilizer, the bagasse, the bleaching water and the alcohol slops are 4.000 \$/t, 200 \$/t, 100 \$/m^3, and 70\$/t, respectively; disposal cost is 90 \$ per ton (supposed equal for all types of waste).

Table 3.12. Numerical data (ton per year).

Main product demand		**Raw material requirement**		**Waste**	
Sugar	450.000 t/y	Fertilizer	19.800 t/y	Bagasse	328.500 t/y
Pulp	70.000 t/y	Bagasse	133.000 t/y	Bleaching water	175.000 m^3/y
Alcohol	25.000 t/y	Bleaching water	50.000 m^3/y	Alcohol slops	20.000 t/y
Fertilizer	30.000 t/y	Alcohol slops	12.000 t/y	Fertilizer waste	3.000 t/y

Table 3.13. Values of the technical coefficients.

Stage	***R***	***W***
A	$0.044\,\frac{t\,fertilizer}{t\,sugar}$	$0.73\,\frac{t\,bagasse}{t\,sugar}$
B	$1.9\,\frac{t\,bagasse}{t\,pulp}$	$2.5\,\frac{m^3\,bleaching\,water}{t\,pulp}$
C	$2\,\frac{m^3\,bleaching\,water}{t\,alcohol}$	$0.8\,\frac{t\,alcohol\,slops}{t\,alcohol}$
D	$0.4\,\frac{t\,alcohol\,slops}{t\,fertilizer}$	$0.1\,\frac{t\,waste\,fertilizer}{t\,fertilizer}$

Table 3.14 displays the values of the contractual parameters α and β in the four scenarios characterized by increasing levels of trust. Table 3.15 shows the simulation results in terms of percentage of IS relationships on the total arising in the case of presence and absence of the contract.

Table 3.14. The value of the contract parameters.

		TRUST = 1		TRUST = 0.75		TRUST = 0.5		TRUST = 0.25	
		α	β	α	β	α	β	α	β
A-B	**σ/μ=0.1**	0.6843	0.5573	0.1181	0.3025	0.3095	0.3886	0.1288	0.3073
	σ/μ=0.2	0.4732	0.5717	0.4001	0.5389	0.3934	0.5359	0.0858	0.3975
	σ/μ=0.3	0.8327	0.7421	0.1684	0.4431	0.126	0.4242	0.3874	0.5418
	σ/μ=0.4	0.4024	0.5173	0.6293	0.6194	0.5872	0.6004	0.1288	0.3073
B-C	**σ/μ=0.1**	0.6245	0.8926	0.5779	0.8507	0.146	0.462	0.3928	0.6841
	σ/μ=0.2	0.1734	0.5341	0.3756	0.716	0.3162	0.6626	0.1949	0.5534
	σ/μ=0.3	0.4687	0.8051	0.2526	0.6106	0.2912	0.6453	0.438	0.7775
	σ/μ=0.4	0.5352	0.8381	0.3664	0.6862	0.2604	0.5908	0.0788	0.4273
C-D	**σ/μ=0.1**	0.3407	0.6538	0.1763	0.4424	0.0627	0.2964	0.3403	0.6532
	σ/μ=0.2	0.2411	0.5747	0.2578	0.5962	0.5083	0.9182	0.1948	0.5151
	σ/μ=0.3	0.3211	0.6606	0.3869	0.7452	0.4139	0.7799	0.3478	0.6949
	σ/μ=0.4	0.261	0.5172	0.4746	0.7917	0.5156	0.8444	0.2898	0.5542
D-A		0	0	0	0	0	0	0	0

Table 3.15. Comparison between the baseline and the contract settings (Percentage of IS relationships on the total).

		TRUST=1			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	85.29%	82.59%	77.36%	73.83%
	NC	73.48%	68.06%	65.01%	64.16%
High T	C	82.23%	70.32%	60.74%	55.05%
	NC	56.53%	47.68%	44.00%	43.02%

		TRUST=0.75			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	85.20%	81.43%	77.34%	71.87%
	NC	73.00%	66.75%	65.12%	63.02%
High T	C	81.63%	68.75%	60.84%	52.08%
	NC	55.47%	46.25%	43.41%	41.14%

		TRUST=0.50			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	84.64%	79.98%	74.33%	69.47%
	NC	71.15%	65.40%	62.59%	60.97%
High T	C	81.74%	67.08%	56.80%	50.86%
	NC	54.06%	45.04%	42.06%	40.16%

		TRUST=0.25			
		Low U	Low-Medium U	Medium-High U	High U
Low T	C	83.87%	78.01%	71.65%	66.42%
	NC	69.56%	63.54%	60.46%	58.38%
High T	C	80.64%	65.34%	55.09%	47.63%
	NC	52.62%	43.76%	41.10%	39.20%

U = Uncertainty; T=Turbulence; C= Presence of Contract; NC=Absence of Contract

3.5 Discussion

Since IS, although beneficial for the system as a whole, could be locally inefficient for the single firm, it requires the establishment of either a central authority imposing IS (the so-called top-down approach) or of a contractual mechanism that incentive firms to spontaneously pursue it, in a self-organized model. In this work I have borrowed this idea from supply chain management literature, where supply chains, like IS networks, exhibit a misalignment incentive problem to integration and I have proposed how to design a proper contract, sharing the benefit between the parties involved in the exchange, which boosts the emergence of a network of stable industrial relationships.

These results contribute to the open discussion in the literature about the role of contractual mechanisms in IS, which is still in its infancy (Chertow et al., 2004). Based on the results of my analysis, I suggest specific attention should be devoted to the design of contractual mechanisms, which, properly defined, can be a facilitator for establishing symbiotic relationships. In particular, I proposed a contract based on a transfer payment re-aligning firm incentives to industrial symbiosis, easy to design and particularly beneficial when demand uncertainty is not high, while turbulence is high. This outcome is particularly relevant because suggests that the adoption of the proposed contract could extend the diffusion of ISNs in new sectors, where the cooperative exchange of resources is not currently adopted.

The effect of trust, even though is not the main focus of the Chapter, merits some comments. My results contribute to show that trust enhances the efficacy of the contract playing a positive moderating role on the emergence of IS, confirming the importance to have trust-based relationships in ISNs (Hewes and Lyons, 2008; Lambert and Boons, 2002).

A further contribution of this Chapter concerns a methodological advance in the study of the self-organized IS. I proposed the application of agent-based simulation to study the spontaneous emergence of industrial symbiosis relationships coupled with a quantitative approach based on the enterprise input-output useful to model the network of symbiotic exchanges. This model, even though proposed for a specific case, is generalizable to any network case. To the best of my knowledge, no study using these approaches have been developed to date to study IS.

My study has certain limits. First, being built on real data, it provides results concerning the context analyzed, which cannot be generalized to every case, even though the proposed methodology, as said above, is completely generalizable. It refers to a network of sequential symbiotic relationships, while the analysis of empirical cases, provided in the theoretical Section, shows that different network typologies exist.

Further research could be focused i) on the study of more complex contractual mechanisms in order to favor the emergence of symbiotic relationships, even in presence of highly uncertain environments, ii) on the improvement of the model of the network of the symbiotic relationships, to include all real cases, iii) on the introduction into the model of the network of social ties linking the firms and the treatment of trust as a dynamic variable resulting from social interactions and evolution of firm.

Chapter 4. Efficiency of industrial symbiosis networks

4.1 Introduction

The topic of efficiency in IS was analyzed in the literature in strong closeness with the economic and environmental benefits provided by such an approach. Scholarly interest in ISN efficiency was due to the awareness that the willingness of firms to be involved in IS relationships is much higher the greater the benefits they obtain from such an approach. Despite the assessment of these benefits is a widespread topic in the literature (see Chapter 1), few theoretical contributions have been provided about definitions and numerical measures of efficiency. Efficiency of ISN was so far addressed by using eco-efficiency indicators at the level of ISN (Park and Behera, 2014; Salmi, 2007). In particular, three generally applicable indicators have been proposed, by dividing the economic performance of firms involved in the ISN (in terms of revenues or value added) for their: i) raw material consumption; ii) energy consumption; and iii) CO_2 emissions. Literature demonstrated that the IS approach is able to enhance eco-efficiency of industrial system by increasing the economic performance and/or by reducing the environmental impact, *ceteris paribus*. However, this approach has two important limitations: i) the impossibility to compare the same indicator for different ISNs, since the scale of the indicator depends on the specific network; and ii) the impossibility of eco-efficiency indicators to provide indications about the extent to which the benefits currently generated could be further increased by better implementing the IS approach. Accordingly with the latter limitation, the possibilities for the evolution of the ISN are not taken into account. Since these limitations, the eco-efficiency indicators are not useful to assess the efficiency of the ISNs. Then, the literature lacks of theoretical concept about the efficiency of ISNs: when an ISN can be considered efficient and how to measure such an efficiency. This Chapter is devoted to fill this gap, defining the concept of "efficiency of ISN" and designing numerical indicators to assess it.

The Chapter is organized as follows. In Section 4.2, the theoretical background of the concept of efficiency in industrial field is presented. In Section 4.3, the concept of "technical exchange efficiency" is proposed, based on the theoretical background previously presented. In Section 4.4, a numerical indicator of such an efficiency is proposed. In Section 4.5, I tested the efficiency measure on two case examples of IS, the former in the industrial field, the latter in the urban field. Finally, in Section 4.6 I discussed the relationship between technical exchange efficiency and economic performance of ISN.

4.2 Theoretical background: Efficiency in industrial field

In order to analyze the concept of efficiency in industrial symbiosis, here I review the studies concerning the efficiency in the industrial field, where this topic has been largely analyzed. This review is not intended to be exhaustive of the studies on the topic, but is aimed to identify definitions and measures of efficiency.

4.2.1 Definition and measure of technical production efficiency

IS is implemented in the industrial context among production processes, each of them uses a given set of inputs to produce one or more outputs. In such a context, the concept of technical production efficiency can be considered (e.g. Agrell and Martin West, 2001; Kapelko et al., 2015; Ma et al., 2002). Such an efficiency can be defined for both a single production process and an industrial system composed by several production processes. In both cases, technical production efficiency addresses how the process/system transforms inputs into outputs. In this regard, let us consider a generic production process requiring two inputs, *x* and *y*, to produce a given output. All the combinations of productive factors that can be technically adopted to produce Π units of output are represented by the part of the Cartesian plane delimited at the bottom by the curve SS' in Figure 4.1. Accordingly, Π units of output can be indifferently produced by using Qx units of input *x* and Qy units of input *y*, by using Rx>Qx units of input *x* and Ry<Qy units of input *y*, or by using Px>Qx units of input *x* and Py>Qy units of input *y*.

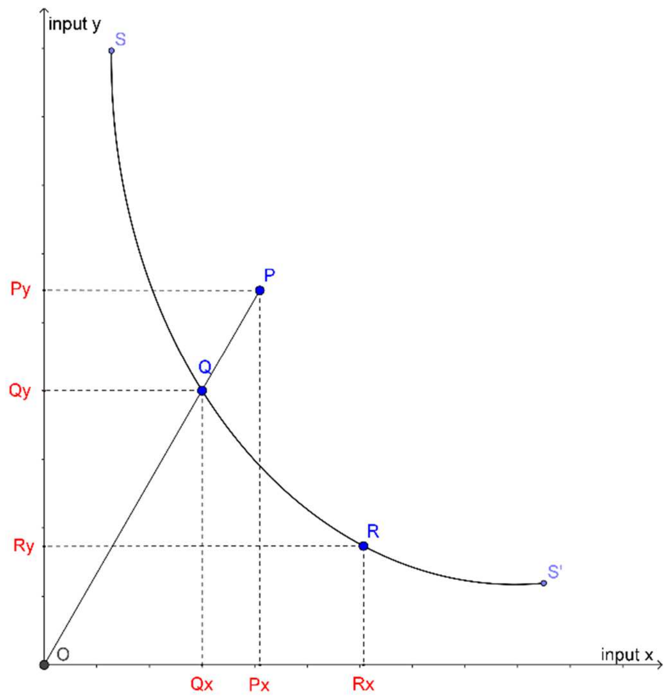


Figure 4.1. Graphical representation of the framework to evaluate technical production efficiency.

Koopmans (1951) first provided a formal definition of a production process technically efficient: "*A producer is technically efficient if an increase in any output requires a reduction in at least one other output or an increase in at least one input, and if a reduction in any input requires an increase in at least one other input or a reduction in at least one* *output*". According to the Koopmans' definition, all the points on the curve SS' are technically efficient: in fact, for all these points, it is not technically possible to produce the same amount of output reducing the amount of input *x* (*y*) without increasing the amount of input *y* (*x*). For this reason, the curve SS' is defined as the efficient production frontier.

Let us consider now the point P in Figure 4.1. According to the Koopmans' definition, such a point is not technically efficient, since the process could produce the same amount of output using lower amount of both inputs *x* and *y*. In this regard, the contributions of Debreu (1951) and Farrell (1957) allowed to develop a measure of technical production efficiency, known as the "Debreu-Farrell measure". Technical production efficiency of generic process can be measured as "*one minus the maximum equiproportionate reduction in all inputs that still allows continued production of given outputs*" (Lovell, 1993, p.10). According to this measure, all the efficient points have technical production efficiency equal to one. Of course, technical production efficiency of process denoted by the point P will be lower than one. It can be measured by using the following equation:

$$TE = 1 - \left(\frac{\overline{\mathrm{QP}}}{\overline{\mathrm{OP}}}\right) \tag{4.1}$$

where $\overline{\mathrm{QP}}$ and $\overline{\mathrm{OP}}$ refer to the segments depicted in Figure 4.1. Hence, the higher the distance between the point P and the efficient production frontier ($\overline{\mathrm{QP}}$), the lower the technical efficiency will be. Although this measure has been referred here to process/system with two inputs and one output, it can be easily extended to processes/systems with N>2 inputs and M>1 outputs (Farrell, 1957).

Firms are interested to adopt technically efficient production methods because, so doing, they minimize production costs. Moreover, the efficient production frontier can change over time, as a result of technological innovation in production methods (Fare et al., 1994). The amount of at least one input required to produce the same amount of output, *ceteris paribus,* can be reduced by such innovations. This case is depicted in Figure 4.2, where the new frontier is denoted as SS". Because of innovation, it is now technically possible to produce Π units of output with Q'x<Qx units of input *x* and Q'y<Qy units of input *y*. Hence, the process denoted by the point Q is no longer technically efficient and its current measure of technical production efficiency becomes lower than one.

Firms are interested to innovate their production processes because, so doing, their economic performance is certainly improved. In fact, costs of inputs are reduced at equal revenues (when the same output is produced using lower inputs) or, conversely, revenues from outputs are increased at equal costs of inputs (when the same inputs allow to produce more output) (Farrell, 1957).

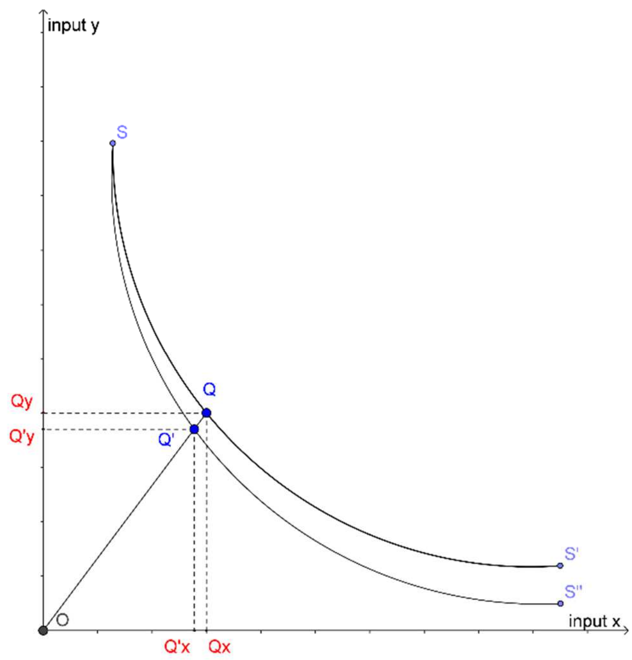


Figure 4.2. Effect of technological innovation on the efficient production frontier.

Moreover, as the environmental issue is gaining more attention, the definition of technical production efficiency can be extended considering wastes generated by production processes/systems as additional inputs (Kuosmanen and Kortelainen, 2004; Reinhard et al., 1999). Hence, at the same level of output, the efficient production frontier for a given process/system can be moved by two kinds of technological innovations: i) innovations allowing to reduce the amount of at least one required input, *ceteris paribus*; ii) innovations allowing to reduce the amount of at least one produced waste, *ceteris paribus*. Basing on the extended definition of technical efficiency, both these kinds of innovation improve the economic performance of the process/system, at the same time reducing its impact on the environment, *ceteris paribus*.

Then, technical production efficiency is related to the performance of the process/system: the efficiency can increase as the result of improvement in this performance. In particular, the efficiency is equal to one when the process/system has the highest reachable performance.

4.2.2 Definition and measure of economic production efficiency

Let us consider the Cartesian plane depicted in Figure 4.1: accordingly, Π units of output can be indifferently produced by using Qx units of input *x* and Qy units of input *y* or by using Rx>Qx units of input *x* and Ry<Qy units of input *y*. Since both the solutions are on the efficient production frontier, their technical production efficiency is equal to one. However, the production cost of these solutions can be different, depending on costs of production factors *x* and *y*. The firm will chose to implement the solution Q if $p_x Q_x + p_y Q_y < p_x R_x + p_y R_y$, where p_x and p_y are the unitary costs of factors x and y, respectively.

Alternatively, if $p_x Q_x + p_y Q_y > p_x R_x + p_y R_y$, the firm will chose to implement the solution R. Moreover, the production frontier allows the existence of the point M, so that $p_x M_x + p_y M_y < p_x F_x + p_y F_y \ \forall \ F \in SS'$. The point M is related to the most convenient solution from the economic point of view, i.e., the solution with the lowest production costs. Such a point is graphically depicted in Figure 4.3. In the same figure, the segment TT' denotes all the points characterized by the same production costs. The allocative efficiency is the measure used to take into account the allocation of productive factors. For the generic point Q, such a measure is defined as follows:

$$AE = 1 - \frac{\overline{MQ}}{\overline{OQ}} \tag{4.2}$$

The allocative efficiency measure assesses the extent to which the firm is using the combination of production factors with the lowest production cost. In particular, it is equal to one if the firm is adopting the combination denoted by the point M, alternatively it is lower than one.

Moreover, the economic efficiency measure for the generic point P can be defined by multiplying technical and allocative efficiency. It results:

$$EE = TE \cdot AE = \left(1 - \frac{\overline{QP}}{\overline{OP}}\right)\left(1 - \frac{\overline{MQ}}{\overline{OQ}}\right) = 1 - \frac{\overline{MP}}{\overline{OP}} \tag{4.3}$$

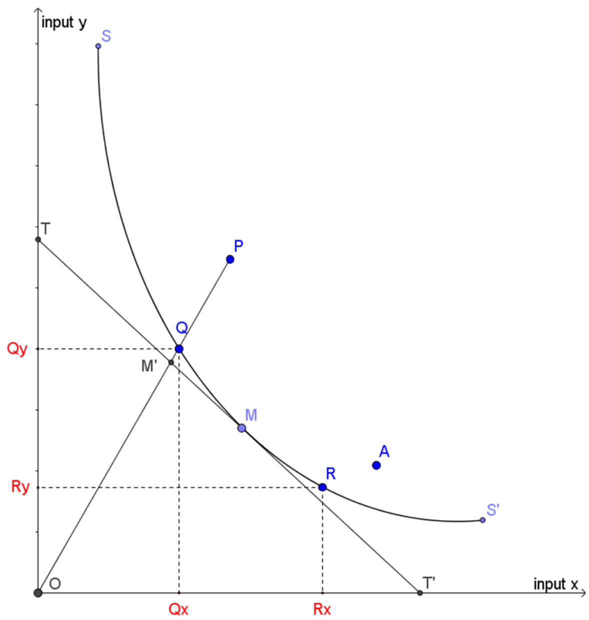


Figure 4.3. Graphical representation of the framework to evaluate economic production efficiency.

Economic efficiency takes into account both technical and allocative efficiency. Such a measure is equal to one when both these efficiencies are equal to one, i.e., when the production process is technically efficient and is producing with the lowest production costs. In fact, even if technical production efficiency is equal to one, in case of allocative efficiency lower than one, the economic efficiency will be lower than one. Moreover, the economic performance is equal to the ratio between the actual economic performance of the production process and the highest achievable one.

4.2.3 The impact of industrial symbiosis on production efficiency

When IS is implemented among processes belonging to an industrial system, the amount of wastes disposed of in the landfill as well as of inputs purchased from outside may be reduced. In such a case, some performance of the system can be enhanced.

Let us consider an industrial system composed of two production processes, A and B. For the sake of simplicity, let us assume that each process produces only one output (O(A) and O(B), respectively), requiring only one primary input (I(A) and I(B)) and producing only one waste (W(A) and W(B)) (Figure 4.4).

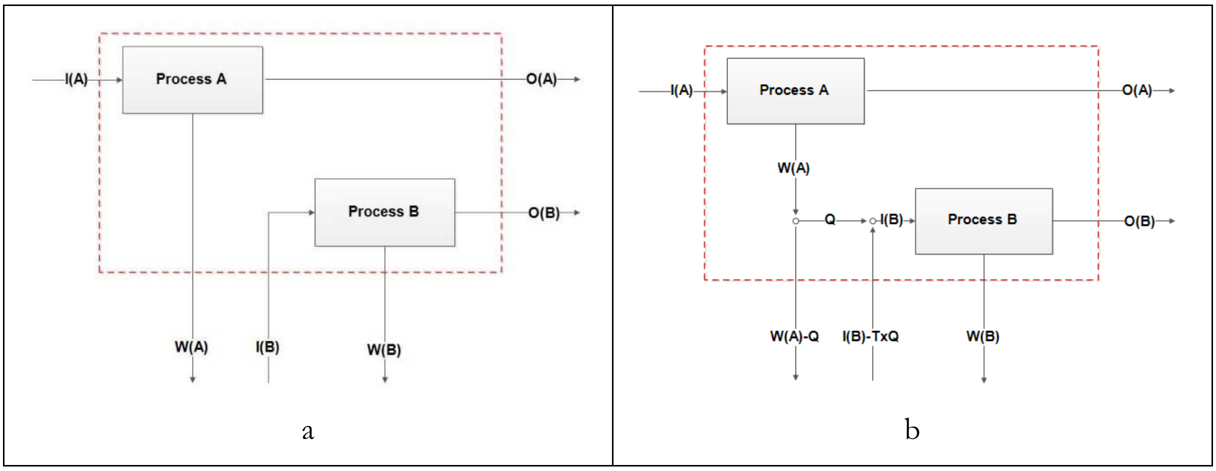


Figure 4.4. Industrial system composed of two production processes, when IS does not occur (a) and when IS occurs (b).

Let us assume that the system is perfectly efficient from the technical point of view, i.e., that no inputs or wastes can be reduced at equal produced output (technical production efficiency of the system is equal to one). In particular, the amount of I(A) required and W(A) generated are directly proportional to the amount of O(A) produced. Similarly, the amount of I(B) required and W(B) generated are directly proportional to amount of O(B) produced. In such a system, there is no substitutability among productive factors, i.e. the current combination of required inputs and produced wastes is the only one able to produce the current amount of outputs. Hence, the efficient production frontier is composed by only one point, denoting the current status of the system in the space $\mathbb{R}^4$ (the number of dimensions is equal to the total number of inputs required and wastes produced by the system).

Let us assume now that feasibility conditions to replace I(B) with W(A) arise. Moreover, let us assume that one unit of W(A) is technically able to replace T units of I(B). Hence, Q units of waste produced by process A can be potentially used to replace TxQ units of input required by process B (Figure 4.4b). In this regard, two different cases may occur: pure substitution and impure substitution.

Pure substitution between W(A) and I(B). Let us consider the Cartesian plane where the x-axis denotes the amount of W(A) disposed of in the landfill and the y-axis denotes the amount of I(B) required from outside the system. For the sake of simplicity, I do not consider the other two dimensions (I(A) and W(B)), since these parameters are not affected by the IS exchange. In such a plane, the point N=(W(A), I(B)) denotes the system when IS does not occur. When Q units of W(A) are exchanged between processes, three different conditions may occur: i) $\mathrm{Q} = \frac{\mathrm{I(B)}}{\mathrm{T}} < W(\mathrm{A})$. Such a case is denoted by the point S=(W(A)-Q, 0) in Figure 4.5a: the system does not purchase any units of I(B) from outside but it has to dispose of in the landfill W(A)-Q units of W(A); ii) $\mathrm{Q} = \mathrm{W(A)} < \frac{\mathrm{I(B)}}{\mathrm{T}}$. Such a case is denoted by the point S=(0, I(B)-TxQ) in the Figure 4.5b: the system does not dispose of in the landfill any units of W(A) but it has to purchase I(B)-TxQ units of I(B) from outside; and iii) $\mathrm{Q} = \mathrm{W(A)} = \frac{\mathrm{I(B)}}{\mathrm{T}}$. Such a case is denoted by the point O in the Figure 4.5c: the system does not purchase any units of I(B) from outside and does not dispose of in the landfill any units of W(A). The achievement of one of these three status depends on two parameters: i) the match between the produced amount of waste W(A) and the required amount of input I(B); and ii) the substitution rate T between waste and input. The angle α in Figure 4.5 is representative of this parameter: the higher T, the lower α will be, *ceteris paribus*[1].

Based on the definition of technical production efficiency, in all the three previous cases the system denoted by the point S is more efficient than the one denoted by the point N: in fact, at equal produced output, the amount of both W(A) disposed and I(B) purchased are lower than in the scenario without IS. This means that in all cases depicted in Figure 4.5, the efficient production frontier has moved due to IS. In fact, the system denoted by the point N, which was efficient before than IS became possible, is currently no longer efficient. Because of the Debreu-Farrell measure, the system denoted by the point S has now efficiency equal to one. All the points on the segment $\overline{\mathrm{SN}}$ become now technically attainable by the system. These points (except for the point S) have technical efficiency lower than one: in particular, the lower the distance from S, the higher the efficiency will be.

[1] In fact, it results:

$$\alpha = \arccos\left\{\mathrm{T}\cdot\frac{\mathrm{I(B)}}{\sqrt{[\mathrm{W(A)}-\mathrm{Q}]^2+\mathrm{I(B)}^2}}\right\} \qquad \text{if } \mathrm{Q} = \frac{\mathrm{I(B)}}{\mathrm{T}} < W(\mathrm{A}) \text{ (Figure 4.5a)}$$

$$\alpha = \arccos\left\{\mathrm{T}\cdot\frac{\mathrm{I(B)}-\mathrm{T}\cdot\mathrm{Q}}{\sqrt{\mathrm{W(A)}^2+[\mathrm{I(B)}-\mathrm{T}\cdot\mathrm{Q}]^2}}\right\} \qquad \text{if } \mathrm{Q} = \mathrm{W(A)} < \frac{\mathrm{I(B)}}{\mathrm{T}} \text{ (Figure 4.5b)}$$

$$\alpha = \arccos\left\{\mathrm{T}\cdot\frac{\mathrm{I(B)}}{\sqrt{\mathrm{W(A)}^2+\mathrm{I(B)}^2}}\right\} \qquad \text{if } \mathrm{Q} = \mathrm{W(A)} = \frac{\mathrm{I(B)}}{\mathrm{T}} \text{ (Figure 4.5c)}$$

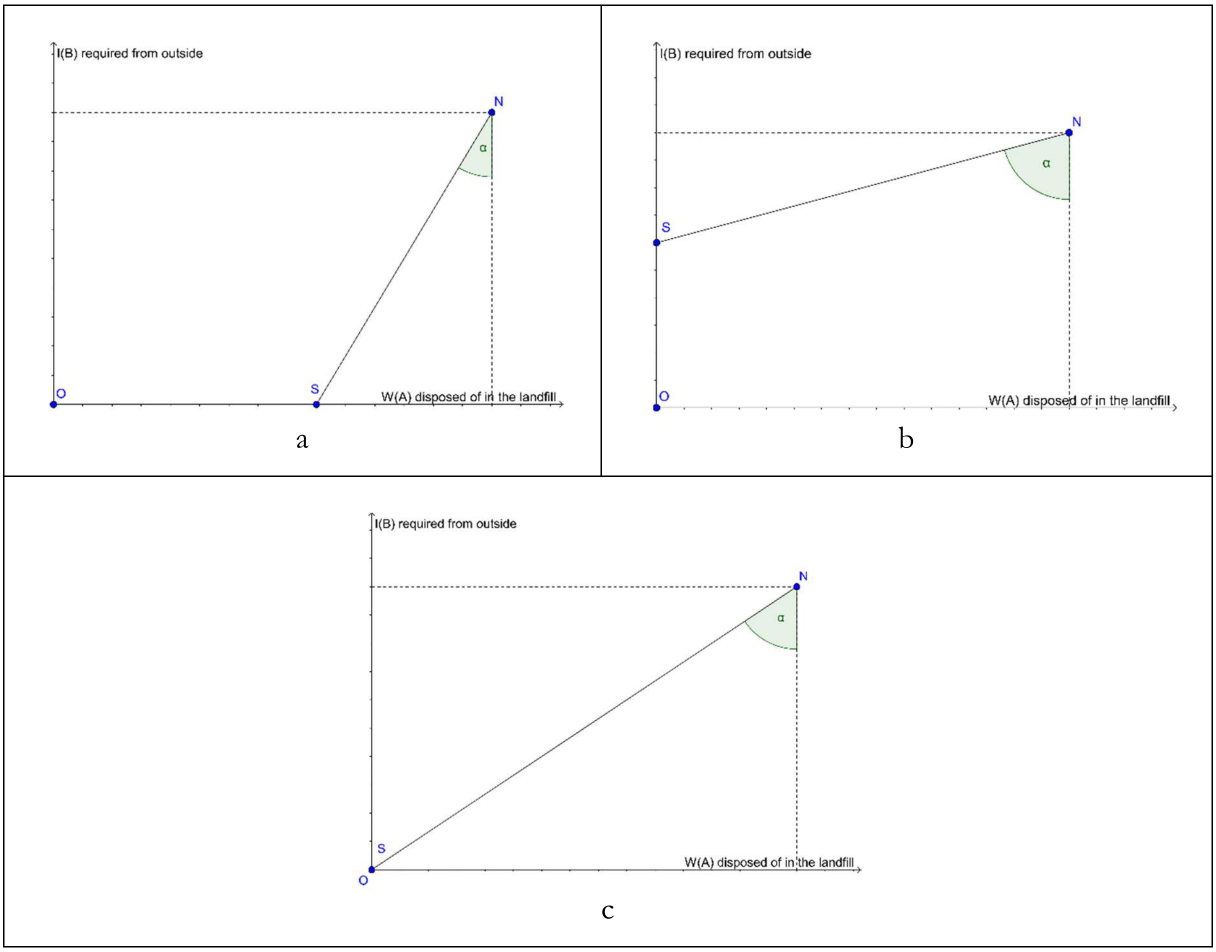


Figure 4.5. Effect of IS (when pure substitution occurs) on the efficient production frontier, in case: $\mathbf{Q = \frac{I(B)}{T} < \mathit{W}(A)}$ (a), $\mathbf{Q = W(A) < \frac{I(B)}{T}}$ (b), $\mathbf{Q = W(A) = \frac{I(B)}{T}}$ (c).

However, differently from the case in Figure 4.2, such a change of the efficient production frontier is not dependent on technological innovation reducing the amount of W(A) generated by process A and the amount of I(B) required by process B at equal produced output. In fact, the amount of both W(A) generated to produce O(A) and I(B) required to produce O(B) remain constant even when IS occurs, *ceteris paribus*. Instead, such a change is due to the possibility provided by the IS to use part of generated W(A) to replace part of required I(B). Hence, in case of pure substitution between W(A) and I(B), production costs are of course reduced for both the processes: therefore, according to the economic logic driving the implementation of the IS approach, the system will implement IS, moving from point N to point S.

Impure substitution between W(A) and I(B). Let us consider now the case when impure substitution between W(A) and I(B) occurs. In such a case, I assume that I(C) units of additional input are needed to exchange Q units of W(A) between processes A and B. In the space depicted in Figure 4.6, the point N=(W(A), I(B), 0) denotes the system when IS does not occur, whereas the point S denotes the system when IS occurs. In particular, three different cases may occur: i) S=(W(A)-Q, 0, I(C)) if $\mathrm{Q} = \frac{\mathrm{I(B)}}{\mathrm{T}} < W(A)$ (Figure 4.6a); ii) S=(0, I(B)-TxQ, I(C)) if $\mathrm{Q} = \mathrm{W(A)} < \frac{\mathrm{I(B)}}{\mathrm{T}}$ (Figure 4.6b); and iii) S=(0, 0, I(C)) if $\mathrm{Q} = \mathrm{W(A)} = \mathrm{I(B)}$ (Figure 4.6c).

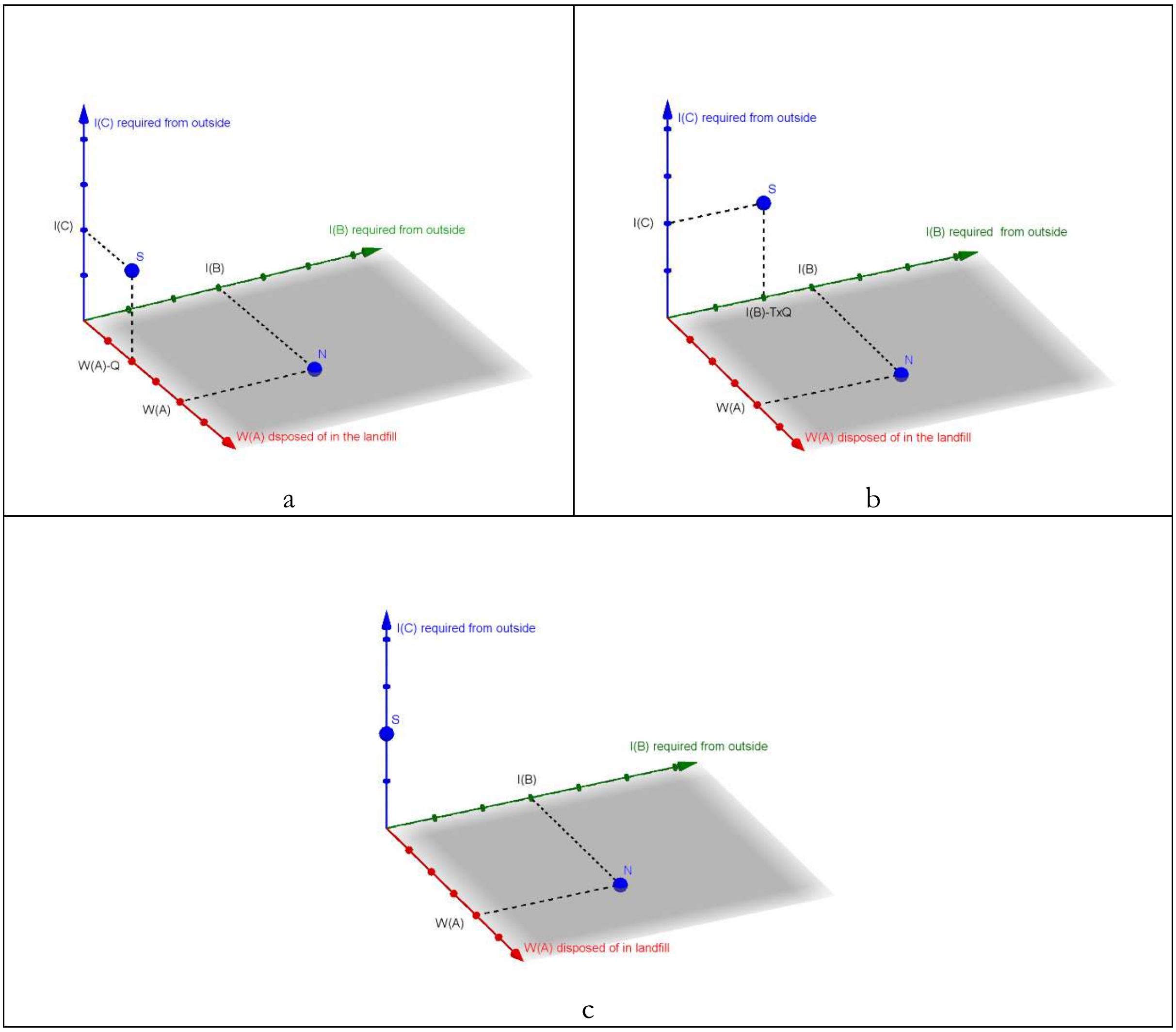


Figure 4.6. Effect of IS (when impure substitution occurs) on the efficient production frontier, in case: $\mathbf{Q = \frac{I(B)}{T} < \mathit{W}(A)}$ (a), $\mathbf{Q = W(A) < \frac{I(B)}{T}}$ (b), $\mathbf{Q = W(A) = \frac{I(B)}{T}}$ (c).

Basing on the Koopmans' definition of technical production efficiency, I can argue that the systems denoted by points N and S in Figure 4.6 are characterized by the same efficiency. In fact, both W(A) disposed of in the landfill and I(B) purchased from outside are reduced by IS, but the symbiotic exchange requires additional input I(C), which is not required when IS does not occur. Hence, in case of impure substitution between W(A) and I(B), IS does not improve the technical production efficiency of the system. However, IS expands the space of production possibilities for the industrial system, making all the points on the segment $\overline{\text{NS}}$ technically reachable by the system. This means that new combinations of production inputs are now available to produce the same amount of output. Nevertheless, on the contrary than the previous case, all the points denoting these combinations have the same technical production efficiency. Assuming that the advantage due to lower costs of input purchase and waste disposal will be higher than the additional costs arising due to IS, the system will implement IS moving from point N to point S.

Previous cases show that IS can affect two performance of ISNs: i) the amount of wastes disposed of in the landfill; and ii) the amount of primary inputs used by production processes. The higher the improvement in these performances, the higher the benefits provided by IS will be. Moreover, the improvement in these performances depends on how waste exchanges allow the match between waste supply and waste demand. For this reason, in defining the concept of efficiency related to IS, I refer to a technical exchange efficiency: such an efficiency focuses on waste exchanges among firms belonging to an ISN, evaluating the extent to which these exchanges are providing benefits.

Taking into account the previous contributions, in the next Section I provide a formal definition of technical exchange efficiency of IS and I propose a measure of such an efficiency.

4.3 The concept of technical exchange efficiency of industrial symbiosis

Let us consider an ISN where only one symbiotic exchange occurs, for instance the one depicted in Figure 4.4b. Assuming that replacing I(B) with W(A) is feasible from the environmental and economic point of view, the higher the amount of W(A) not disposed of in the landfill and the amount of I(B) not purchased from outside due to IS, the higher the benefits provided to the ISN by the IS approach will be. In particular, the highest benefits that such an exchange can provide are those arising when the overall amount of the produced waste is not disposed of in the landfill and contemporaneously the overall amount of the required input is not purchased from outside the ISN because replaced by the waste. Therefore, I argue that the ISN is efficient from the symbiotic exchange point of view if, as a result of implementing IS among its processes, the ISN does not dispose of in the landfill any units of wastes and, at the same time, does not purchase from outside any units of inputs[2]. Such a condition has been defined as "perfect symbiosis" by Yazan et al. (2016b). Therefore, as a corollary, I can argue that the ISN is efficient from the exchange point of view if perfect symbiosis occurs.

Let us consider the industrial system in Figure 4.4b. Such a system can be represented in the Cartesian plane where the x-axis denotes the amount of W(A) disposed of in the landfill whereas the y-axis denotes the amount of W(A) equivalent to the amount of I(B) required by the ISN. In such a plane, the system when IS does not occur can be represented by the point N=(W(A),I(B)/T). According to the definition of technical exchange efficiency, the ISN is efficient when Q=W(A)=I(B)/T. In such a case, the system will be denoted by the point O=(0,0). Let us consider now the case where Q=I(B)/T<W(A). Perfect symbiosis does not occur because the system has to dispose of in the landfill W(A)-Q units of waste. The point denoting the system when symbiosis occurs is S=(W(A)-Q,0). Perfect symbiosis would occur when, from the geometrical point of view, S≡O: in such a condition, no difference between angles α and β in Figure 4.7 would occur ($\alpha=\beta$). Hence, the point S (ISN when symbiosis occurs) is much more distant from the point O (condition of perfect symbiosis) when $|\alpha-\beta|$ is higher. The segment $\overline{PN}$ in Figure 4.7 is obtained by rotating the segment $\overline{ON}$ by the angle $\beta-\alpha$ anticlockwise. It can be demonstrated that the segment $\overline{PS}$ is proportional to $|\alpha-\beta|$: the higher the difference between α and β, the longer $\overline{PS}$ will be. Such a framework

[2] In such a definition, only exchanged wastes and replaced inputs are considered.

can be used to propose a measure of technical exchange efficiency for the considered ISN defined by the following equation:

$$e = \frac{\overline{SN}}{\overline{ON}} \tag{4.4}$$

since $\overline{ON} = \overline{PN}$. Accordingly, technical exchange efficiency ranges between zero and one. In particular, it is equal to zero when symbiosis does not occur within the ISN (S≡N and therefore $\overline{SN} = 0$) whereas is equal to one when perfect symbiosis occurs (S≡O and therefore $\overline{SN} = \overline{SO}$). Moreover, the higher the distance between points S and P, the lower the technical exchange efficiency will be.

Actually, the ISN depicted by point S is technically efficient from the production point of view but is not technically efficient from the symbiotic exchange point of view. This is due to the structure of the ISN, which does not allow the complete match between the amount of produced waste and the amount of required input. However, technical exchange efficiency can be increased by modifying the current structure of the ISN. In this regard, two kinds of structural changes can be implemented to increase technical exchange efficiency: i) reducing the amount of W(A) produced within the ISN; and ii) increasing the amount of I(B) required within the ISN. The former change can be obtained through technological innovation reducing the amount of W(A) generated to produce one unit of output O(A), *ceteris paribus*. The latter change can be obtained by increasing the amount of O(B) produced, *ceteris paribus*. In both cases, I can observe that lower amount of W(A) will be disposed of in the landfill. Moreover, from the geometrical point of view, $|\alpha-\beta|$ decreases.

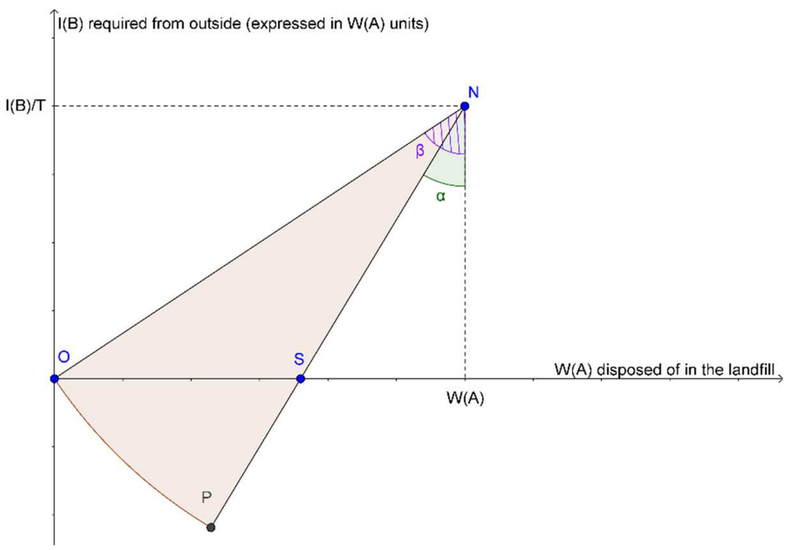


Figure 4.7. Graphical representation of the concept of technical exchange efficiency of IS.

It can be noted that one waste may replace more than one input within the ISN. In this regard, let us suppose that in a generic ISN W(A) can indifferently replace the two inputs I(B) and I(C). In such a case, the overall amount of required inputs can be expressed in terms of the equivalent amount of W(A). Hence, also this case can be depicted on the Cartesian plane shown in Figure 4.7. The point denoting the system when symbiosis does not occur will be N=(W(A), I(B)/T_{AB}+I(C)/T_{AC}), where T_{AB} and T_{AC} denote how many units of inputs I(B) and I(C) can be replaced by one unit of W(A), respectively. Assuming that, when IS occurs, W(A) replaces 40% of I(B) and 50% of I(C), the point denoting such a condition will be S=(0, 0.4*I(B)/T_{AB}+0.5*I(C)/T_{AC}). Also in this case, technical exchange efficiency can be computed by using Equation 4.4.

Technical exchange efficiency of IS can be a useful tool to drive the evolution of the existing ISNs, aimed to improve the current performance of existing industrial systems. In addition, new industrial systems with high performance can be built by designing ISNs with high technical exchange efficiency, where production processes are highly integrated among them from the IS point of view. Such new systems based on IS approach can have lower environmental impact than the traditional ones since they are able to better use resources within them.

4.4 Measuring technical exchange efficiency for industrial symbiosis networks

In this section, I discuss about how to measure the technical exchange efficiency for a generic ISN composed of a given set of production processes.

In order to model the ISN, I use an input-output approach at the enterprise level. In particular, I first use the Enterprise Input-Output (EIO) model (Lin and Polenske, 1998; Albino et al., 2002; Albino et al., 2003) to shape primary input requirement and waste production by each production process. Then, I design the extension of the general EIO model to take into account also the symbiotic flows among production processes (Section 4.4.1). Afterward, I show how to measure technical exchange efficiency by using data from the EIO model (Section 4.4.2).

4.4.1 Enterprise Input-Output model for industrial symbiosis networks

General EIO model. The EIO model describes the ISN as a network of production processes using an input–output approach. In general, a network of production processes consists of processes that procure materials and energy (primary inputs), transform them into outputs, and produce wastes. Two kinds of outputs can be produced: i) intermediate goods, destined to be used as input by other processes; ii) final goods for external markets. Hence, each process uses primary inputs from external markets and intermediate goods from other processes to produce outputs. Moreover, the wastes generated are disposed of in the landfill.

A generic ISN is made of *n* processes. For the sake of simplicity, I assume that each process produces only one main output. This output can be: i) all sold on final markets; ii) all used as intermediate good by other processes; and iii) in part sold on final markets and in part used as intermediate good by other processes. Hence, each process has to produce output to satisfy: i) the final demand from external markets; and ii) the internal demand from other processes. In this regard, let f_0 be the $n \times 1$ vector of the final demand from external markets and x_0 the $n \times 1$ vector of gross outputs. Moreover, let Z_0 be the $n \times n$ matrix of the domestic intermediate deliveries, where the generic element $Z_{0_{ij}}$ denotes the amount of output produced by process *i* and used as intermediate good by process *j*. Then, the following identity holds:

$$x_0 = (I - Z_0 \cdot \hat{x}_0^{-1}) \cdot f_0 \tag{4.5}$$

where I is the $n \times n$ identity matrix and a "hat" is used to denote a diagonal matrix where $\hat{x}_{0_{ii}} = x_{0_i}$ $\forall$ *i* and $\hat{x}_{0_{ij}} = 0 \;\; \forall\, i \neq j$. In case of no flows of intermediate goods occur between processes ($Z_0 = \vec{0}$), the gross output of each process has only to satisfy the corresponding final demand ($x_0 = f_0$).

To produce its output, the process i requires $n(r_i)$ primary inputs and generates $n(w_i)$ wastes. The network as a whole requires $n(r)$ primary inputs, with $n(r) \leq \sum_{i=1}^{n} n(r_i)$, and generates $n(w)$ wastes, with $n(w) \leq \sum_{i=1}^{n} n(w_i)$. Equality holds when either each primary input is used by only one process or each waste is produced by only one process, respectively.

Let r_0 be the $n(r) \times 1$ vector of primary inputs used in production processes and let w_0 be the $n(w) \times 1$ vector of wastes generated by production processes. Both primary inputs requirement and wastes production are related to the gross outputs by the following equations:

$$r_0 = R x_0 \tag{4.6}$$

$$w_0 = W x_0 \tag{4.7}$$

where the $n(r) \times n$ matrix of primary input coefficient R and the $n(w) \times n$ matrix of waste output coefficients W are obtained from observed data. The generic element R_{lj} denotes the quantity of primary input l required to produce one unit of the output of process j. Similarly, the element W_{kj} denotes the quantity of waste k generated to produce one unit of the output of process j.

When a new final demand f $(n \times 1)$ occurs for the ISN, I assume that matrices R and W remain constant. Then, I have a new gross output vector x $(n \times 1)$ based on Equation 4.8 and, consequently, I can compute new vectors r $(n(r) \times 1)$ and w $(n(w) \times 1)$ from Equations 4.9 and 4.10.

$$x = (I - Z_0 \cdot \hat{x}_0^{-1}) \cdot f \tag{4.8}$$

$$r = Rx \tag{4.9}$$

$$w = Wx \tag{4.10}$$

EIO model for IS exchanges. When IS occurs, wastes of a process can be used to replace primary inputs in other processes. Then, in an ISN, processes can exchange among them intermediate goods and wastes for primary inputs. In particular, wastes of each production process can be either disposed of in the landfill or used as primary inputs by other processes. Each process can either purchase primary inputs from outside the ISN or use wastes from other processes as primary inputs. An ISN can be fully described if, for each production process, all the flows of primary inputs, intermediate goods, outputs, and wastes from and to both the other processes and the external markets are identified.

In order to model waste flows taking place among processes, for each couple of processes *i* and *j* I can define e^{ij} as the $n(w)\times 1$ vector of the observed symbiotic flows between *i* and *j*. The generic element e_k^{ij} denotes the amount of the *k*-th waste flowing from process *i* to process *j*.

Taking into account such a symbiotic exchange, two different cases may happen: i) pure substitution between waste *k* and primary input *l*; ii) impure substitution between waste *k* and primary input *l*.

In case of pure substitution among waste and primary input, the waste can be directly used in place of primary input. If one unit of waste *k* generated by process *i* can replace P_{lk}^{ij} units of primary input *l* required by process *j*, e_k^{ij} units of waste *k* produced by process *i* replace $P_{lk}^{ij} \cdot e_k^{ij}$ units of primary input *l* in process *j*.

In case of impure substitution among waste and primary input, the waste has to be treated before being used as primary input. In the EIO approach, such a treatment is modeled as a process transforming wastes (input of treatment processes) in primary inputs (output of treatment processes). In Figure 4.8, the treatment process transforming waste *k* generated by process *i* in primary input *l* required by process *j* is graphically depicted. Let RT_{pk}^{ij} be the amount of additional input *p* required to treat one unit of waste *k* and WT_{mk}^{ij} the amount of additional waste *m* generated by treating one unit of waste *k*. Hence, treating e_k^{ij} units of waste *k* requires $RT_{pk}^{ij} \cdot e_k^{ij}$ units of additional inputs *p* and generates $WT_{mk}^{ij} \cdot e_k^{ij}$ units of additional waste *m*.

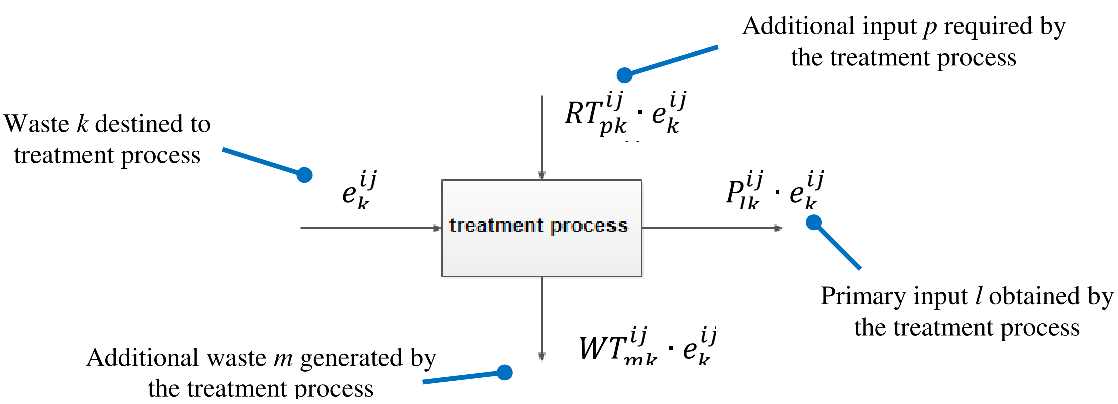


Figure 4.8. Graphical representation of the *k*-th waste treatment process in the ISN model.

Considering now the ISN as a whole, I can compute the environmental benefits due to the IS approach by using the EIO model. First, the $n(w)\times 1$ vector w^S of wastes saved, i.e. not disposed of in the landfill, is computed by using the following equation:

$$w^S = \sum_{i=1}^{n}\sum_{j=1}^{n} e^{ij} \tag{4.11}$$

Then, the $n(r)\times 1$ vector r^S of primary inputs saved, i.e. replaced by wastes and hence not purchased from outside the ISN, is computed by using the following equation:

$$r^S = \sum_{i=1}^{n}\sum_{j=1}^{n} P^{ij} \cdot e^{ij} \tag{4.12}$$

where P^{ij} is the $n(r)\times n(w)$ matrix denoting substitution rates among wastes produced by process *i* and primary inputs required by process *j*. The generic element P_{lk}^{ij} denotes how many units of primary input *l* are replaced by one unit of waste *k*.

Assuming that treatment processes generate $n(tw)$ additional wastes and require $n(tr)$ additional inputs, I can compute the $n(tw)\times 1$ vector of additional wastes generated (w^T) and the $n(tr)\times 1$ vector of additional inputs required (r^T) by the treatment processes by using the following equations:

$$w^T = \sum_{i=1}^{n}\sum_{j=1}^{n} WT^{ij} \cdot e^{ij} \tag{4.13}$$

$$r^T = \sum_{i=1}^{n}\sum_{j=1}^{n} RT^{ij} \cdot e^{ij} \tag{4.14}$$

where WT^{ij} is the $n(tw)\times n(w)$ matrix modelling waste generation by treatment processes and RT^{ij} is the $n(tr)\times n(w)$ matrix modelling input requirement by treatment processes.

Finally, let us consider the symbiotic exchange between processes *i* and *j*, where waste *k* replaces primary input *l*. In general, I highlight that the amount of exchanged waste cannot be higher than the amount of waste produced by process *i*. At the same time, such quantity cannot be higher than the correspondent amount of replaced input that is required by the process *j*. From numerical point of view, the following condition must be verified:

$$e_k^{ij} \leq \min\left\{W_{ki}x_i; \frac{R_{lj}}{P_{kl}^{ij}} \cdot x_j\right\} \quad \forall\,(i,j,k,l), \qquad P_{kl}^{ij} \neq 0 \tag{4.15}$$

4.4.2 Technical exchange efficiency measures

Let us consider the generic ISN where n(w) wastes are exchanged. For the sake of simplicity in mathematical notation, let us assume that each waste is able to replace only one primary input. Hence, it results that $\mathrm{n(w)} = \mathrm{n(r)}$. Let w^E be the $n(w)\times 1$ vector of wastes equivalent to the input requirement. Such a vector is computed by using the following equation:

$$w^E = \left[\left(\sum_{i=1}^{n}\sum_{j=1}^{n} P^{ij}\right)^{-1}\right]^T \cdot (Rx) \tag{4.16}$$

where the generic element w_k^E denotes how many units of w_k are equivalent to the required amount of the input that waste *k* can replace.

Then, in the space $\mathbb{R}^{n(r)+n(w)} = \mathbb{R}^{2\cdot n(w)}$ I can identify the point $\mathrm{N} = (\mathrm{w_1, w_2, \dots, w_{n(w)}, w_1^E, w_2^E, \dots, w_{n(w)}^E})$, denoting the ISN when no symbiotic exchanges occur, and the point $\mathrm{S} = (\mathrm{w_1 - w_1^S, w_2 - w_2^S, \dots, w_{n(w)} - w_{n(w)}^S, w_1^E - w_1^S, w_2^E - w_2^S, \dots, w_{n(w)}^E - w_{n(w)}^S})$, denoting the ISN when IS occurs. Technical exchange efficiency can be computed by using the following equation, which is the generalization in the multi-dimension space of the Equation 4.4:

$$e = \frac{\left|\overrightarrow{\mathrm{N - S}}\right|}{\left|\overrightarrow{\mathrm{N - O}}\right|} \tag{4.17}$$

where $\overrightarrow{\mathrm{N - O}} = (\mathrm{w_1, w_2, \dots, w_{n(w)}, w_1^E, w_2^E, \dots, w_{n(w)}^E})$ and $\overrightarrow{\mathrm{N - S}} = (\mathrm{w_1^S, w_2^S, \dots, w_{n(w)}^S, w_1^S, w_2^S, \dots, w_{n(w)}^S})$. Similarly to the case discussed in Section 3 for a two-dimension case, e values range between zero and one. In particular, $e = 0$ when $\mathrm{S} \equiv \mathrm{N}$ whereas $e = 1$ when $\mathrm{S} \equiv 0$. Moreover, the higher $\left|\overrightarrow{\mathrm{N - S}}\right|$, i.e., the lower the distance from the point O, *ceteris paribus*, the higher the technical exchange efficiency will be.

Using such a framework, I can decompose e in two further measures, which separately take into account the technical exchange efficiency for the wastes not disposed of in the landfill, e^W, and for the primary inputs saved, e^{PI}. Let us consider $\mathbb{R}^{n(w)}$ and $\mathbb{R}^{n(r)}$ as two vector subspaces of $\mathbb{R}^{n(w)+n(r)}$. In the former, the point $\mathrm{N_w} = (\mathrm{w_1, w_2, \dots, w_{n(w)}})$ has coordinates equal to the amount of all the produced wastes when IS does not occur, whereas the point $\mathrm{S_w} = (\mathrm{w_1 - w_1^S, w_2 - w_2^S, \dots, w_{n(w)} - w_{n(w)}^S})$ has coordinates equal to the amount of the wastes disposed of in the landfill when IS occurs. Similarly, in the latter space, the point $\mathrm{N_{pi}} = (\mathrm{w_1^E, w_2^E, \dots, w_{n(w)}^E})$ has coordinates equal to the amount of all primary inputs required by the ISN when IS does not occur, whereas the point $\mathrm{S_{pi}} = (\mathrm{w_1^E - w_1^S, w_2^E - w_2^S, \dots, w_{n(w)}^E -}$

$\mathrm{w}^{\mathrm{S}}_{\mathrm{n(w)}}$) has coordinates equal to the amount of all primary inputs purchased from outside the ISN when IS occurs. e^{W} and e^{PI} can be computed by using the following equations:

$$e^{W} = \frac{\left|\overrightarrow{\mathrm{N_w} - \mathrm{S_w}}\right|}{\left|\overrightarrow{\mathrm{N_w} - \mathrm{O_w}}\right|} \tag{4.18}$$

$$e^{PI} = \frac{\left|\overrightarrow{\mathrm{N_{pi}} - \mathrm{S_{pi}}}\right|}{\left|\overrightarrow{\mathrm{N_{pi}} - \mathrm{O_{pi}}}\right|} \tag{4.19}$$

Both the measures range between zero and one. They are equal to zero when IS does not occur. In particular, e^{W} measures how ISN is efficient in reducing wastes disposal of in the landfill. It is equal to one when $\mathrm{S_w} \equiv \mathrm{O_w}$, i.e. when no wastes produced by the ISN are disposed of in the landfill, being recovered by symbiotic exchanges. Similarly, e^{PI} measures how ISN is technically efficient in reducing primary inputs purchasing from outside the network. This measure is equal to one when $\mathrm{S_{pi}} \equiv \mathrm{O_{pi}}$, i.e. when the primary inputs requirement of ISN is entirely satisfied by the wastes recovered within the network.

The efficiency measures previously identified can be also used to classify ISNs about their structural characteristics. Such a kind of classification is needed in order to understand how different structural attributes influence the exchanges of wastes and to better identify the strengths and weaknesses of a given ISN (Zhang et al., 2015). I identify three kinds of ISNs:

- **Waste absorbing ISNs**. They are characterized by $e^{PI} \ll e^{W}$ as the waste supply is much lower than the waste demand. Hence, the ISN has high performance in avoiding that wastes could be disposed of in the landfill but it shows low performance in saving the primary inputs (Figure 4.9a);
- **Primary input saving ISNs**. They are characterized by $e^{PI} \gg e^{W}$ as the waste supply is much higher than the waste demand. Hence, the ISN has high performance in saving the primary inputs but it shows low performance in avoiding that wastes could be disposed of in the landfill (Figure 4.9b);
- **Balanced ISNs**. They are characterized by $e^{PI} \cong e^{W}$ as there is an equilibrium between the waste supply and the waste demand. Hence, the ISN has quite similar performance in avoiding that wastes could be disposed of in the landfill and in saving the primary inputs (Figure 4.9c).

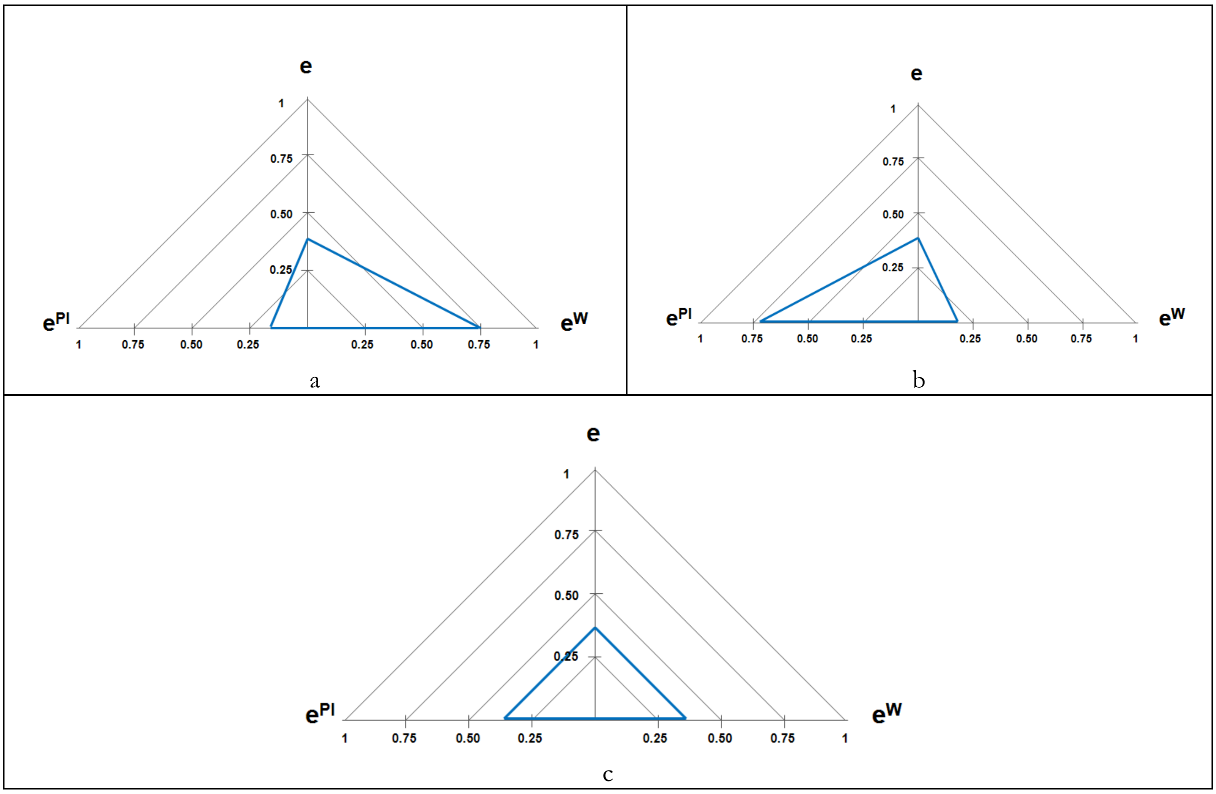


Figure 4.9. Graphical representation of the proposed ISN classification: (a) waste absorbing ISN; (b) primary input saving ISN; (c) balanced ISN. The same value of technical exchange efficiency can be obtained by ISNs with different e^W and e^{PI}.

4.5 Applications

I propose two applications to show how to practically compute technical exchange efficiency. The former concerns a case example of IS in the industrial field (Section 4.5.1). The latter concerns a case example of IS in the urban field (Section 4.5.2).

4.5.1 Industrial symbiosis in industrial field

The analyzed ISN is composed of four production processes (n=4): exhausted tires collection (process 1), cement production (process 2), synthetic grass production (process 3), and iron and steel production (process 4). No flows of intermediate goods occur among processes, so as the gross output of each process has only to satisfy the correspondent final demand. The gross output yearly generated by each process (vector x) is reported in Table 4.1.

Table 4.1. Observed gross output per year of each main product.

Main product	Gross output
Exhausted tires (x_1)	300 t
Cement (x_2)	3000 t
Synthetic grass (x_3)	300000 m²
Iron and steel (x_4)	1000 t

For the sake of simplicity, only wastes and primary inputs that can be involved in symbiotic exchanges are considered. The Process 1 generates two kinds of wastes from exhausted tires collection: carcasses (w_1) and wheel rims (w_2). On the side of inputs, coal (r_1), resilient granules (r_2), and iron (r_3) are required by Process 2, Process 3, and Process 4, respectively. It results $\mathrm{n(w)} = 2$ and $\mathrm{n(r)} = 3$. Assuming that tires consist in 50% carcass and 50% wheel rim, 0.5 tons of carcasses and 0.5 tons of wheel rims are produced for each ton of collected tires. Moreover, producing 1 ton of cement requires 0.063 tons of coal, whereas producing 1 m² of synthetic grass requires $1.05 \cdot 10^{-4}$ tons of resilient granules (Albino and Yazan, 2013). Finally, I assume that 1 ton of iron is needed to produce 1 ton of steel. Hence, it results:

$$\mathrm{W} = \begin{pmatrix} 0.5 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 \end{pmatrix} \qquad \mathrm{R} = \begin{pmatrix} 0 & 0.063 & 0 & 0 \\ 0 & 0 & 1.05 \cdot 10^{-4} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

According to Equations 4.6 and 4.7, the primary inputs required (vector *r*) and the wastes produced (vector *w*) are reported in Table 4.2.

Table 4.2. Amount of required primary inputs and produced wastes by each process.

		Process 1	Process 2	Process 3	Process 4
PRIMARY INPUT					
Coal	r_1		189 t		
Resilient granules	r_2			31.5 t	
Iron	r_3				1000 t
WASTE					
Carcasses	w_1	150 t			
Wheel rims	w_2	150 t			

Carcasses can replace both coal and resilient granules. In this regard, the practice of substituting fossil fuels as coal with ground tires is widespread in the cement industry (Albino et al., 2011; Kääntee et al., 2004). Positive environmental effects of such a practice have been recognized in form of reducing net CO_2 and NO_x emissions in comparison to using fossil fuels (Cook and Kemm, 2004; European Cement Association, 2009; IEA, 2009). According to Corti and Lombardi (2004), 1 ton of tires can replace 0.877 tons of coal. Moreover, the use of exhausted tires as a substitute of resilient granules in synthetic grass production is recognized as positive from the environmental point of view. In this regard, 1 ton of exhausted tires is assumed to replace 0.8 tons of resilient granules (Albino and Yazan, 2013). Finally, I assume one ton of wheel rim replaces one ton of iron. Accordingly, it results:

$$P^{12} = \begin{pmatrix} 0.877 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad P^{13} = \begin{pmatrix} 0 & 0 \\ 0.8 & 0 \\ 0 & 0 \end{pmatrix} \qquad P^{14} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix}$$

For the sake of simplicity, I assume that pure substitution is possible for each symbiotic exchange.

The analyzed ISN is depicted in Figure 4.10, where only wastes and primary inputs that can be involved in symbiotic exchanges are represented.

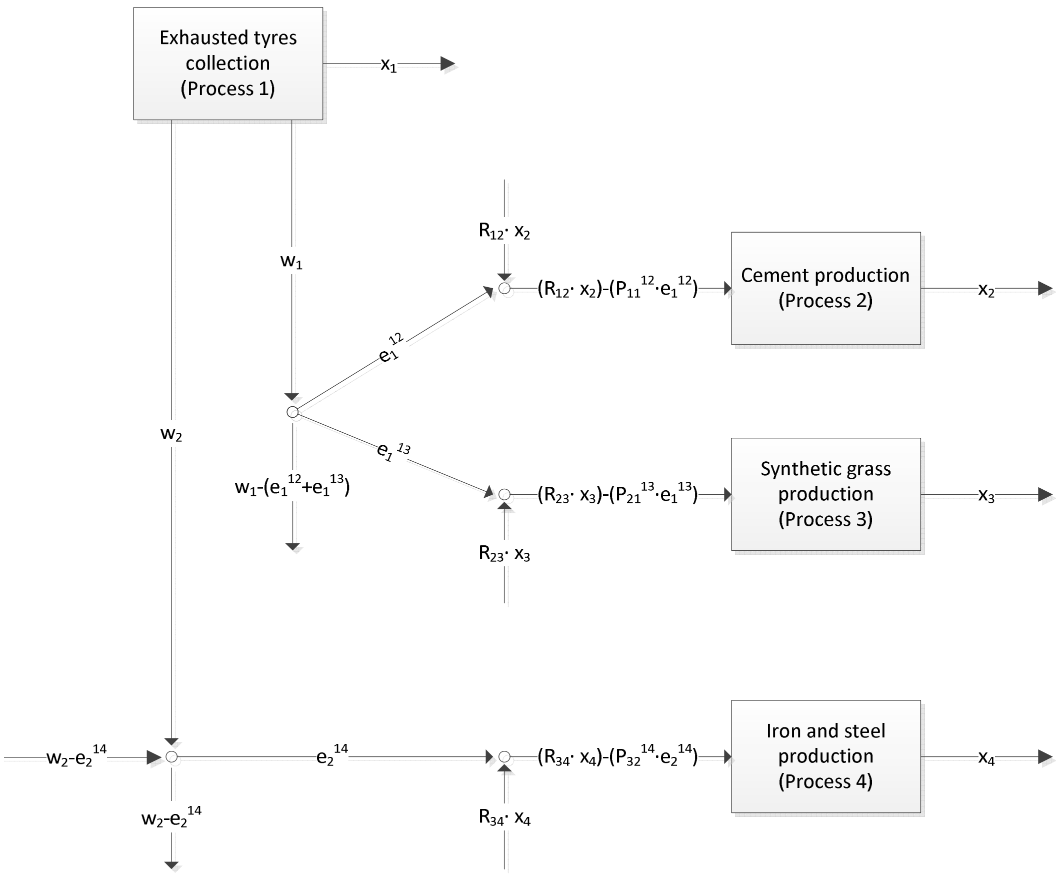


Figure 4.10. EIO graphical representation of the analyzed ISN.

If the Process 1 chooses the Process 2 as the first co-operator, then Process 2 will be supplied with priority. Accordingly, Process 1 will send 150 tons of carcasses to Process 2 whereas any tons of exhausted tires will be sent to Process 3. Moreover, the Process 1 sends 150 tons of wheel rims to Process 4. According to the EIO model in Section 4.4.1, it results:

$$e^{12} = \begin{pmatrix}150\\0\end{pmatrix} \qquad e^{13} = \begin{pmatrix}0\\0\end{pmatrix} \qquad e^{13} = \begin{pmatrix}0\\150\end{pmatrix}$$

Hence, 150 tons of carcasses and 150 tons of wheel rims are not disposed of in the landfill due to IS. In fact, from Equation 4.11, it results:

$$w^S = e^{12} + e^{13} + e^{14} = \begin{pmatrix}150\\150\end{pmatrix}$$

Accordingly, 131.55 tons of coal are replaced by carcasses and 150 tons of iron are replaced by wheel rims. The vector of wastes equivalent to primary input required can be computed by using Equation 4.16. It results:

$$w^E = [(P^{12} + P^{13} + P^{14})^{-1}]^T \cdot (R \cdot x) = \begin{pmatrix}254.88\\1000\end{pmatrix}$$

This means that the overall amount of coal and resilient granules required within the ISN can be replaced by 254.88 tons of carcasses. Similarly, 1000 tons of wheel rims are required to replace all the iron used within the ISN.

I can compute the amount of primary inputs saved by using Equation 4.12. It results:

$$r^S = P^{12} \cdot e^{12} + P^{13} \cdot e^{13} + P^{14} \cdot e^{14} = \begin{pmatrix}131.55\\0\\150\end{pmatrix}$$

In the vector space $\mathbb{R}^{n(w)+n(r)=2\cdot n(w)}$ I can define the point N=(150, 150, 254.88, 1000), denoting the ISN when IS does not occur, and the point S=(0, 0, 104.88, 850), denoting the ISN when IS occurs. Technical exchange efficiency can be computed by using Equation 4.17 In this case, it results $\overrightarrow{\mathrm{N}-\mathrm{S}} = (150, 150, 150, 150)$ and $\overrightarrow{\mathrm{N}-0} = (150, 150, 254.88, 1000)$.

$$e = \frac{\left|\overrightarrow{\mathrm{N}-\mathrm{S}}\right|}{\left|\overrightarrow{\mathrm{N}-0}\right|} = \frac{300}{1053.55} = 0.2847$$

Efficiencies e^W and e^{PI} can be computed using Equations 4.18 and 4.19, respectively. It results $e^W = 1$ and $e^{PI} = 0.2056$. Graphical representation of the three measures is provided in Figure 4.11.

The ISN has technical exchange efficiency equal to 0.2847. In particular, the ISN has high down-stream efficiency $(e^W = 1)$, meaning that symbiotic exchanges are very effective in reducing the amount of wastes disposed of in the landfill. However, the up-stream efficiency is low ($e^{PI} = 0.2056$), meaning that low performance in reducing the amount of primary inputs purchased is achieved. In fact, nevertheless the

69.6% (150*0.877/189) of coal is replaced by carcasses, no amount of synthetic grass is saved and only the 15% (150/1000) of the required iron is replaced by wheel rims. According to the classification proposed in Section 4.2, this ISN can be actually considered as a "waste absorbing network". Then, a strong difference between the amount of produced wastes and the amount of required primary inputs is observed.

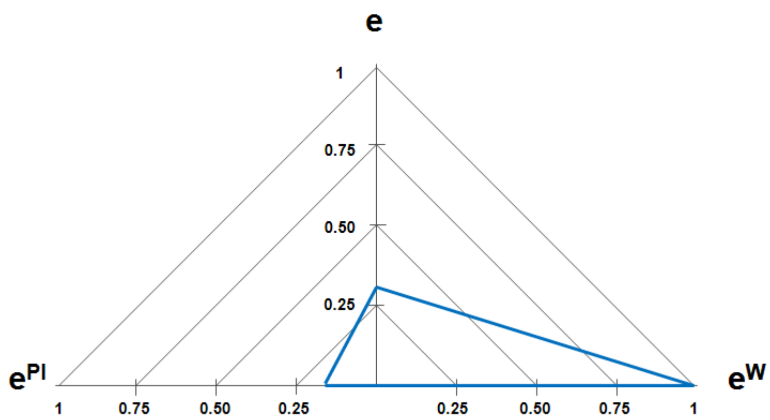


Figure 4.11. Graphical representation of the three efficiency measures for the analyzed ISN.

Technical exchange efficiency can be increased by reducing such a difference. As the waste production is lower than the corresponding demand, the amount of wastes produced and exchanged within the ISN has to be increased. In turn, based on Equation 4.7, the amount of x_1 (collected tires) has to be increased. In this regard, in Figure 4.12, the three measures of technical exchange efficiency are depicted as a function of the amount of collected tires, *ceteris paribus*. Three different parts of the plane may be noted:

- As long as $x_1 \leq 500$ t, e^W remains equal to one and e^{PI} increases. This is because all the additional amount of produced wastes replaces primary inputs: hence, the amount of primary inputs purchased from outside the ISN is reduced. As an overall result, *e* increases;
- As long as $500 \text{ t} < x_1 \leq 2000$ t, *e* continues to increase with lower growth rate. In particular, all the additional amount of wheel rims replaces iron in Process 4: therefore, since the amount of iron purchased from outside the ISN is reduced, e^{PI} increases. However, now the amount of produced carcasses has become higher than the correspondent demand. Therefore, part of produced carcasses has to be disposed of in the landfill. As a result, e^W decreases. As a whole, since the amount of disposed carcasses is lower than the amount of saved iron, *e* increases;
- When $x_1 > 2000$ t, the demand of all the required primary inputs is entirely satisfied by the wastes available within the ISN: hence, e^{PI} becomes equal to one. However, the additional amount of both wastes produced have to be disposed of in the landfill: therefore, e^W decreases, causing that also *e* decreases.

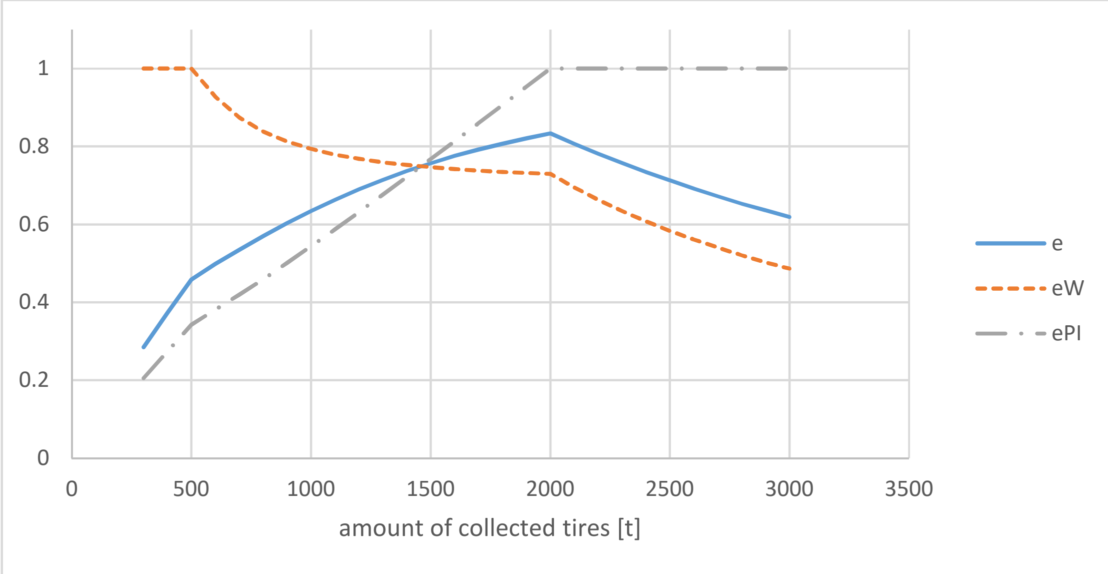


Figure 4.12. Technical exchange efficiency (e), down-stream efficiency (e^W), and up-stream efficiency (e^{PI}) of the ISN as a function of the amount of collected tires.

Figure 4.12 also shows that increasing the amount of collected tires, *ceteris paribus*, does not allow the ISN to achieve the condition of perfect symbiosis. In fact, the highest level of *e* achievable is lower than one. Perfect symbiosis occurs when the amount of each produced waste has to be equal to the correspondent amount demanded. Such a condition can be formalized by the following system of equations (Yazan et al., 2016b):

$$\begin{cases} w_1 = r_1 + r_2 \Rightarrow W_{11}x_1 = \dfrac{R_{12}x_2}{P_{11}} + \dfrac{R_{23}x_3}{P_{12}} \\ w_2 = r_3 \qquad \Rightarrow W_{21}x_1 = \dfrac{R_{34}x_4}{P_{23}} \end{cases} \tag{4.20}$$

In particular, W_{11}, R_{12}, P_{11}, R_{23}, P_{12}, W_{21}, R_{34}, and P_{23} are constant. Hence, solving for x, it results:

$$\begin{cases} 0.5x_1 = 0.0718x_2 + 1.31 \cdot 10^{-4}x_3 \\ 0.5x_1 = x_4 \end{cases}$$

In this case, ∞^2 solutions exist. In Table 4.3, one of the possible solutions (for instance, that obtained by defining *a priori* the levels of x_3 and x_4) is shown.

Table 4.3. Final demand for each production process ensuring the perfect symbiosis among processes.

Process	New final demand	Variation rather the current situation
1	6000 t	+ 5700 t
2	41210 t	+ 38210 t
3	300000 m²	+ 0 m²
4	3000 t	+ 2000 t

Based on this solution, final demands of Processes 1, 2, and 4 have to be increased by 5700 t, 38210 t, and 2000 t, respectively, rather than the current levels. Such an increase could be obtained by adopting two different strategies: i) creating additional demand for outputs produced by firms currently involved in the ISN; and ii) including new firms within the ISN with the same production processes than those currently involved (tires collection, cement production, steel production). Alternatively, the final demand of process 3 does not need to be increased. Figure 4.13 shows the current values of efficiency (blue line) as well as the highest value achievable (green lines).

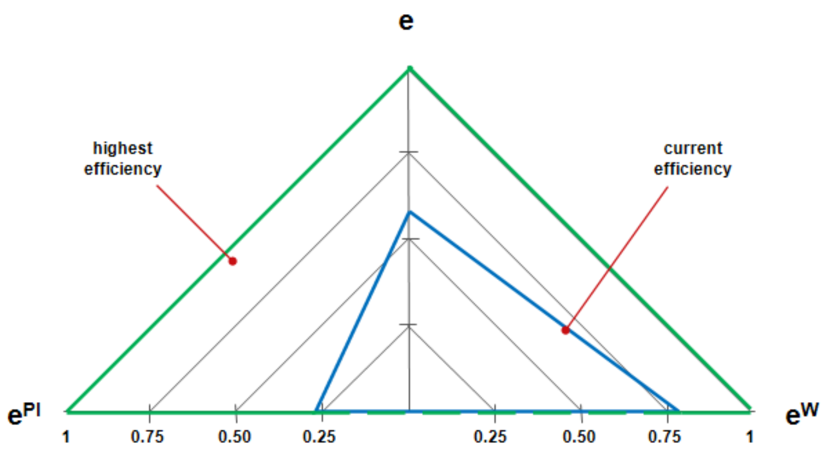


Figure 4.13. Graphical comparison between current efficiency (blue line) and highest efficiency achievable (green line).

Finally, notice that the condition of perfect symbiosis can be achieved by this ISN because the system in Equation 4.20 is solvable under the constraint that none of the x is equal to zero. In fact, a given x equal to zero means that the correspondent process has to be eliminated from the ISN. Alternatively, if the system cannot be solved under such a constraint, the condition of perfect symbiosis cannot be achieved. In this regard, let us consider for instance the ISN depicted in Figure 4.14, where a closed-loop symbiotic exchange exists, i.e. waste from Process A is used by Process B and waste from Process B is used by Process A.

The condition of perfect symbiosis can be mathematically described by the following equation system:

$$\begin{cases} P^{AB} \cdot W_A \cdot x_A - R_B \cdot x_B = 0 \\ -R_A \cdot x_A + P^{BA} \cdot W_B \cdot x_B = 0 \end{cases}$$

In particular, such a condition can be achieved if $\frac{x_A}{x_B} = \frac{R_B}{p^{AB} \cdot W_A} = \frac{p^{BA} \cdot W_B}{R_A}$. Alternatively, if such an identity is not verified, the only solution for the system will be $x_A = x_B = 0$: therefore, perfect symbiosis cannot be achieved by this ISN, due to the current structure of symbiotic exchanges.

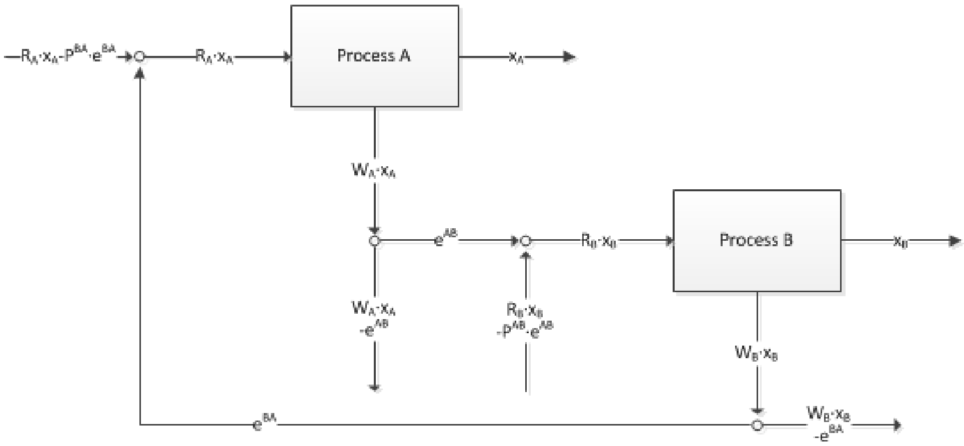


Figure 4.14. Example of ISN with closed-loop symbiotic exchange.

4.5.2 Industrial symbiosis in urban field

Despite the IS approach is typical of industrial contexts, an increasing part of the literature is investigating the adoption of such an approach in the urban field. This phenomenon is driven by the awareness that cities are growing to unprecedented sizes, both in developed and in developing countries. In fact, whereas in 1900 only 10% of the global population were urban dwellers, nowadays that percentage has been risen to 50%, and in 2050 cities could host two-third of the world population (United Nations, 2013). These rapid changes are generating negative impacts on city sustainability, in particular from the environmental point of view. In fact, cities actually consume a large amount of energy and produce a high quantity of wastes (Satterthwaite, 2008; The World Bank, 2012). In this regard, the current global urban wastes production counts approximately 1,3 billion tons per year (The World Bank, 2012) and 60% of produced wastes is disposed of in the landfill. The use of landfills to dispose urban waste is largely adopted both in low-income and in high-income countries, like the United States and many European countries (EPA, 2014; EUROSTAT, 2014; The World Bank, 2012). Even the two most populated countries in the world, China and India, make extensive use of landfills, where over the 80% of their municipal solid waste (MSW) is disposed of (Chen et al., 2010; Sharholy et al., 2008). Moreover, the polluting role of cities is further critical if we consider the expected future trends. Recent estimations preview that cities will use 80% of global energy by 2040 (Shell International BV, 2014) and will double waste production by 2025 (The World Bank, 2012).

Global efforts are in force to solve both energy and waste problems. About energy problem, the main actions have been oriented to efficiency improvements in energy production and replacement of fossil fuels by various sources of renewable energy (Lund, 2007). The main strategies to address waste problem follow two directions: i) decreasing per capita rates of both materials consumption and wastes production (Li et al., 2013; Zsigraiova et al., 2013); ii) making the system circular through the recovering of urban wastes as inputs (Jabbour et al., 2014). The IS approach is a tool to follow the latter strategy. Accordingly, some urban wastes can be transformed in new products or in energy rather than landfilled. Since the possibility to use the huge part of these new products and this energy within the same cities, it is possible to generate different urban resource-closed loops. Thereby, IS could be a useful strategy to improve the environmental performance of cities.

For different kinds of urban wastes, several IS processes may be adopted. Organic wastes, which constitute 46% of wastes produced within cities, can be valued in electric and thermal energy or for fertilizer production (Mata-Alvarez et al., 2000). Paper and cardboard wastes (17% of urban wastes) can be exploited for manufacture of recycled paper or incinerated for energy recovery (Madu et al., 2002). Plastic wastes (10% of urban wastes) can be used to generate new plastic products or exploited for fuel and energy production (Al-Salem et al., 2009). Glass wastes (5% of urban waste) can be used to generate new glass products or recycled in concrete production (Shayan and Xu, 2004). Textiles wastes can be recycled for reuse of fiber (Woolridge et al., 2006). Finally, wood wastes can be used in new wood products or incinerated for energy recovery (Falk and McKeever, 2004). All these processes and relative outputs are shown in Table 4.4.

In this section, I focus on the energy production from urban wastes. Despite of the capacity of all MSW to produce electric energy, I limit the analysis to organic waste for two main reasons. The first is that organic waste is the principal component of MSW, accounting for almost the 50% of all MSW produced. The second reason is that all MSW except organic waste can be managed in a more sustainable way than energy recovery, according to the European Waste Framework Directive (2008/98/EC). In fact, the Directive recommends waste prevention as the most sustainable approach, followed by reusing, recycling, energy recovery, and disposal, ordered by decreasing sustainability degree.

Following the IS approach, organic waste is collected and addressed to waste-to-energy facilities. Thereby, the IS chain involves three phases: waste production, waste collection, and waste-to-energy production.

Waste production is due to four urban processes, i.e. household consumption (Process 1), food retail (Process 2), food service (Process 3), and green areas maintenance (Process 4) (BIO Intelligence Services, 2013; Parfitt et al., 2010). The first three processes produce food waste whereas the last generates yard waste. Each process only has one output: people served (household consumption and food retail), number of meals served (food service), and square meters of green area (green areas maintenance). A technical production coefficient points out how many units of waste are generated by one unit of process output during a certain period of time. Moreover, electric energy consumption is modeled by one process (Process 5) having people served as output. Hence, greater the dimension of urban processes (i.e., the amount of process output) and greater the amount of waste produced and electric energy required, *ceteris paribus*. Collection phase and waste-to-energy production are modeled as a treatment process transforming organic waste into electric energy. Despite the availability of different technological solutions (anaerobic digestion pyrolysis, gasification) to produce electric energy from wastes (Ahmed and Gupta, 2010; Mata-Alvarez et al., 2000), I assume that an anaerobic digestion process is adopted, since anaerobic digestion seems to ensure the highest performance from both an environmental and an economic point of view (Miller and Moyle, 2014). Moreover, for the sake of simplicity, I do not consider fuel consumption required by waste collection, as well as GHG emissions due to the same phase. All these processes are graphically shown in Figure 4.15.

Table 4.4. Possible IS processes for each urban waste.

Urban waste		Symbiotic processes	Outputs	Reference
Paper and cardboard	Paper scraps, packaging, newspapers, boxes, beverage cups	Recycling for reuse of fiber and manufacture of recycled paper or paperboard	Paper products	(Madu et al., 2002)
		Incineration for energy recovery	Energy	
Plastics	Bottles, packaging, containers, bags, cups	Recovery to produce products of the similar material	Plastic products	(Al-Salem et al., 2009)
		Chemical treatment to produce fuel	Fuel	
		Incineration for energy recovery	Energy	
Glass	Bottles, broken glassware, light bulbs	Recycling to produce glass products	Glass products	(Shayan and Xu, 2004)
		Recycling in concrete production	Concrete	
Organic waste	Food waste from households, canteens, restaurants, yard wastes	Recovery for energy production (e.g. anaerobic digestion, pyrolysis)	Energy	(Mata-Alvarez et al., 2000)
		Recovery for fertilizer production (e.g. composting)	Fertilizer	
Textiles	Clothes	Recycling for reuse of fiber	Textiles products	(Woolridge et al., 2006)
Wood	Packaging, yard waste	Recovery in wood products	Wood products	(Falk and McKeever, 2004)
		Recovery for energy production (e.g., incineration, anaerobic digestion)	Energy	

I use real data to characterize waste production and input consumption from numerical point of view. In particular, I assume that each people served produces 46 Kg of food waste (w_1) from household consumption and 8 Kg from food retail (BIO Intelligence Services, 2013), 0.12 Kg of food waste are generated for each served meal (Marthinsen et al., 2012; Silvennoinen et al., 2012), and finally 3 Kg of yard waste (w_2) are generated by maintenance of 1 m^2 of green area (Giacetti, 2008). Moreover, I assume that each citizen uses 2200 kWh of electric energy (r_1) per year. From the EIO point of view, it results:

$$W = \begin{pmatrix} 46 & 8 & 0.12 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 0 & 0 & 0 & 0 & 2200 \end{pmatrix}$$

I assumed that 1.384 and 0.346 kWh of energy can be obtained by treating one kilogram of food waste and yard waste, respectively[3]. It results:

$$P^{15} = P^{25} = P^{35} = \begin{pmatrix} 1.3840 \\ 0 \end{pmatrix} \qquad P^{45} = \begin{pmatrix} 0 \\ 0.3460 \end{pmatrix}$$

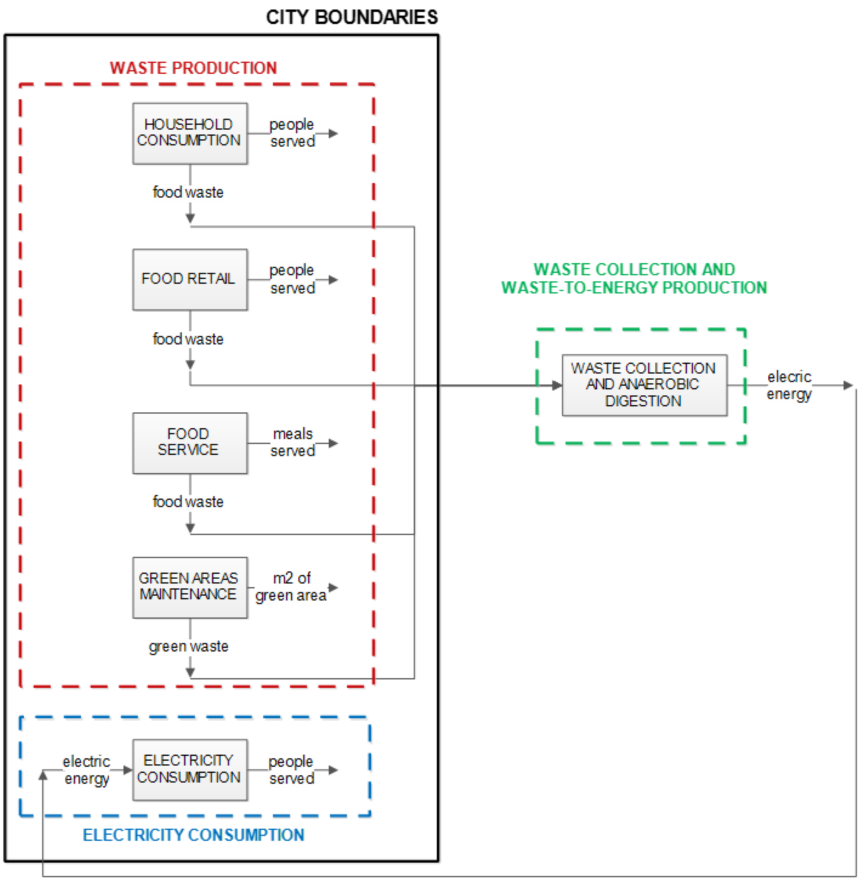


Figure 4.15. EIO representation for the urban model of IS.

[3] I have assumed 0.4 Nm^3 and 0.1 Nm^3 of bio-methane produced per unit of food waste and yard waste, respectively, relying on technical data of existing plants, 8.500 Kcal/m^3 as heating value of bio methane, and 0.35 as efficiency of cogeneration plant, under the hypothesis to burn all methane produced.

Let us consider a generic city whose gross output yearly generated by each process (vector *x*) is reported in Table 4.5. I am considering a small city, characterized by large availability of green areas (100 m² per capita).

Table 4.5. Values of gross output for each process.

Main product	Gross output
People served (x_1)	20000
Meals served (x_2)	900000
m² of green area maintained (x_3)	2000000 m²

The amount of primary input required and waste produced are reported in Table 4.6.

Table 4.6. Amount of required primary inputs and produced wastes by each process.

		Process 1	Process 2	Process 3	Process 4	Process 5
PRIMARY INPUT						
Electric energy [kWh]	r_1					$3.3 \cdot 10^7$
WASTE						
Food waste [Kg]	w_1	$9.2 \cdot 10^5$	$1.6 \cdot 10^5$	$1.08 \cdot 10^5$		
Yard waste [Kg]	w_2				$6 \cdot 10^6$	

Symbiotic flows among processes are modeled by the following vectors:

$$e^{15} = \begin{pmatrix} 9.2 \cdot 10^5 \\ 0 \end{pmatrix} \qquad e^{25} = \begin{pmatrix} 1.6 \cdot 10^5 \\ 0 \end{pmatrix} \qquad e^{35} = \begin{pmatrix} 1.08 \cdot 10^5 \\ 0 \end{pmatrix} \qquad e^{45} = \begin{pmatrix} 0 \\ 6 \cdot 10^6 \end{pmatrix}$$

The amount of wastes not landfilled (w^S) as well as the amount of electric energy produced from such wastes (w^E) are computed by using the following equations:

$$w^S = e^{15} + e^{25} + e^{35} + e^{45} = \begin{pmatrix} 1.188 \cdot 10^6 \\ 6 \cdot 10^6 \end{pmatrix}$$

$$w^E = [(P^{15} + P^{25} + P^{35} + P^{45})^{-1}]^T \cdot (R \cdot x) = (3.72 \cdot 10^6)$$

As a whole, $7.188 \cdot 10^6$ Kg of organic wastes ($1.188 \cdot 10^6$ Kg of food waste and $6 \cdot 10^6$ Kg of yard waste) are not landfilled, and $3.72 \cdot 10^6$ kWh of electric energy are produced.

Technical exchange efficiency can be computed by using Equation 4.17. It results $e = 0.1156$. Moreover, $e^R = 0.1127$ and $e^W = 1$.

I repeated the computations for other two cities (B and C), assuming that all the produced wastes are transformed into electric energy. In particular, B is a small town characterized by significant flow of tourists which results in a greater use of restaurants (greater number of meals served). Finally, C may be a town marked by a greater use of canteens and low availability of green areas per capita (20 m^2). Values of process output as well as technical exchange efficiency are reported in Table 4.7.

Table 4.7. Technical exchange efficiency computed for cities B and C.

	City B	**City C**
People served (x_1)	30000	300000
Meals served (x_2)	5200000	21500000
m^2 of green area maintained (x_3)	1500000	6000000
Technical exchange efficiency	**0.096**	**0.067**

For urban cases, technical exchange efficiency can be a useful parameter since it provides a numerical measure about how the IS approach is contemporaneously addressing waste and energy problems. Moreover, in such a case, e^W is equal to the percentage of organic wastes used to produce energy rather than the total amount produced. Similarly, e^R denotes the percentage of electric energy demand replaced by energy from wastes.

In this regard, I note that symbiotic efficiency keeps quite low values (0.1156, 0.096, and 0.067, respectively), despite e^W is always equal to one. This means that applying IS approach, cities are still far from perfect symbiosis, the condition that allows to fully deal with waste and energy problems. This occurs because IS approach reveals to be effectiveness in mitigating waste disposal problem whereas it ensures poor performance in solving the electric energy problem.

Moreover, the EIO model highlights the main possible actions in order to improve technical exchange efficiency, so further enhancing environmental sustainability of cities: i) increase the number of meals served (x_2); ii) increase the square meters of urban green areas maintained (x_3); iii) increase the food waste production coefficients (W_{11}, W_{12}, W_{13}); iv) increase the yard waste production coefficient (W_{24}); v) reduce the electric energy requirement coefficient (R_{15}); vi) increase the energy production from waste coefficient (P). However, not all these measures are good actions from the ethical point of view. In particular, trying to increase the food waste production coefficients is completely wrong. Instead, policymakers at urban level could aim to increase the square meters of urban green areas, with preference for those ensuring high amount of yard wastes, and force to increase energy savings.

4.6 The concept and the measure of economic exchange efficiency for industrial symbiosis networks

Increasing technical exchange efficiency of a given ISN, the amount of wastes not disposed of in the landfill and of inputs not purchased from outside the ISN are increased. Therefore, the gross economic benefits generated by the IS practice are enhanced. These benefits (*GEB*) can be computed by using the following equation:

$$GEB = pc^T \cdot r^S + dc^T \cdot w^S \tag{4.21}$$

where *pc* is the $n(r)\times 1$ vector of primary input purchase costs and *dc* is the $n(w)\times 1$ vector of waste disposal costs. In particular, the generic element pc_l is the cost to purchase one unit of the *l*-th input and dc_k is the cost to landfill one unit of the *k*-th waste.

However, additional costs arise, eroding these benefits: transportation costs and transaction costs. According to Table 2.6, it results:

$$TC = \sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij} \cdot \left[\left(utc^{ij}\right)^T \cdot e^{ij}\right] \tag{4.22}$$

$$CC = \sum_{i=1}^{n}\sum_{j=1}^{n} cc_{i\to j} \tag{4.23}$$

where d_{ij} is the distance between firms *i* and *j*, utc^{ij} is the $n(w)$x1 vector of unitary transportation costs (the generic utc_k^{ij} denotes the cost to transport one unit of waste *k* from firm *i* to firm *j*

Moreover, in case of impure substitution (see Section 4.2.3), additional processes are needed to treat wastes. In such a case, the costs of inputs required and wastes produced by these processes have to be considered. These costs (*RC*) can be computed by using the following equation:

$$RC = \alpha \sum_{i=1}^{n}\sum_{j=1}^{n} \left(URC^{ij}\right)^T \cdot e^{ij} \tag{4.24}$$

where URC^{ij} is the $n(w)$x$n(r)$ matrix of treatment costs (the generic URC_{kl}^{ij} denotes the cost to treat one unit of waste *k* produced by the process *i* destined to replace input *l* in process *j*), and α is the 1x$n(r)$ unitary vector.

Under the hypothesis that each IS relationship is economically convenient for all the involved firms, the growth in gross economic benefits due to higher technical production efficiency is higher than the growth of additional costs associated. Therefore, according to eco-efficiency indicators, increasing the technical exchange efficiency of a given ISN results in enhancing the eco-efficiency of such a network.

Maximizing the technical exchange efficiency results in maximization of the gross economic benefits stemming from the IS practice. However, applications discussed in Section 4.5 showed that different structures of symbiotic exchanges for a given ISN are able to ensure the same level of technical exchange efficiency. This is supported by some contributions offered by the literature, which recognize that different configuration of a given ISN can guarantee the same gross economic benefits (because of the equal amount of input saved and wastes not landfilled) with different costs associated. These costs erode the gross economic benefits generated by the IS exchanges for firms, then reducing the economic performance of the ISN. Moreover, these contributions are aimed to design the best structure of symbiotic exchanges within a given ISN able to minimize the additional costs stemming from IS relationships, at equal amount of input saved and wastes not landfilled (Aviso et al., 2010; Cimren et al., 2011; Gonela and Zhang, 2014; Hipólito-Valencia et al., 2014; Kim et al., 2010; Lim and Park, 2010; Rubio-Castro et al., 2010). Despite these contributions address specific ISNs, results converge in suggesting that, *ceteris paribus*, the additional costs stemming from the IS practice can be minimized by minimizing the redundancy of symbiotic exchanges. It means that each firm should send each waste it produces to only one other firm, as well as it should receive each waste is used by only one other firm. In such a way, firms can minimize transaction costs stemming from the IS relationships.

Therefore, the highest economic performance of the ISN can be achieved only if the following two conditions occur: i) the ISN is characterized by the perfect symbiosis condition, i.e., if technical exchange efficiency is equal to one; ii) costs needed to implement IS are the minimum possible. Such a performance can be computed as follows:

$$EP^{MAX} = pc^T \cdot r + dc^T \cdot w - (TC + RC + CC)^{MIN} \tag{4.25}$$

where the term $(TC + RC + CC)^{MIN}$ stands for the minimum combination of symbiotic costs.

According to the framework for the industrial field, the economic efficiency of ISN can be computed by using the following equation:

$$ee = \frac{EP}{EP^{MAX}} = \frac{pc^T \cdot r^S + dc^T \cdot w^S - (TC + RC + CC)}{pc^T \cdot r + dc^T \cdot w - (TC + R + CC)^{MIN}} \tag{4.26}$$

Of course, such an efficiency ranges between zero and one. Moreover, the economic efficiency can be decomposed as follows:

$$ee = \frac{pc^T \cdot r^S + dc^T \cdot w^S}{pc^T \cdot r + dc^T \cdot w} \cdot \frac{1 - \dfrac{TC + RC + CC}{pc^T \cdot r^S + dc^T \cdot w^S}}{1 - \dfrac{(TC + RC + CC)^{MIN}}{pc^T \cdot r + dc^T \cdot w}} \tag{4.27}$$

The first term denotes the technical exchange efficiency measured in economic terms. It is equal to one only if technical exchange efficiency is equal to one (i.e., if $r^S = r$ and $w^S = w$). The second term is the ratio between two parameters. The former denotes the incidence of symbiotic costs to the economic benefits generated by the symbiotic exchanges. The latter denotes the incidence of the minimum symbiotic costs on the maximum economic benefits achievable. Both these parameters range between zero and one. Moreover, whilst the latter term is fixed, the former depends on the actual configuration of symbiotic exchanges.

According to this framework, the economic efficiency is equal to one only if the following conditions contemporaneously are guaranteed: i) technical exchange efficiency is equal to one; ii) the ISN has the configuration allowing the minimum level of symbiotic cost, i.e., $TC + RC + CC = (TC + RC + CC)^{MIN}$.

4.7 Discussion

The two case study analyzed in Section 4.5 were useful to test the application of the proposed indices to real analysis, showing practical applications of the measures of technical exchange efficiency. In fact, the proposed measure can be useful: i) as a communication tool conveying information to firms and stakeholders about the extent to which IS is currently providing benefits rather than its potential one; and ii) as a tool supporting the design and evolution phases of ISNs. By measuring technical exchange efficiency, the mismatches between demand and supply of each exchanged waste can be easily discovered. Afterward, strategies aimed to reduce these mismatches can be designed (suggested) by using the EIO model.

This study extends the literature on efficiency in the IS field. Previous studies consider this topic, but focusing on the assessment of the economic and environmental benefits generated by the IS practice. In this regard, I show that, maximizing technical exchange efficiency of an ISN, the amount of wastes disposed of in the landfill and the amount of inputs purchased from outside can be minimized. Therefore, natural resources can be exploited more efficiently within the network. Moreover, increasing technical exchange efficiency, the gross economic benefits created by the ISN are enhanced, *ceteris paribus*. For these reasons, it is important that ISNs are characterized by high technical exchange efficiency.

However, the maximization of technical exchange efficiency is not enough to maximize the economic benefits that firms gain from the IS approach. In fact, whilst such a maximization results in the maximization of the gross economic benefits stemming from the IS practice, it does not provide any indications about the additional costs associated with the IS practice. Previous contributions in the literature suggested that the additional costs can be cut down by minimizing the redundancy of symbiotic exchanges. In this regard, in order to support the choice of the best evolution strategy for the ISN, I introduced the measure of economic efficiency taking into account both these issues. Economic exchange efficiency takes into account the overall economic benefits generated by the ISN rather than the highest benefits that the ISN is able to generate. Hence, in order to guarantee that ISNs are characterized by high economic efficiency, these networks have to be characterized by high technical exchange efficiency (thereby, a strong match between demand and supply of wastes has to be ensured) and low level of redundancy of the IS exchanges among firms.

Finally, the main limit of this approach is due to the high amount of data needed for the analysis. Moreover, these data have to be collected from different sources, i.e., from each firm belonging to the ISN. This could be a hard task, since firms can be unwilling to spread their confidential data. Such a weakness has to be properly addressed in the future.

Chapter 5. Resilience of industrial symbiosis networks

5.1 Introduction

Studies on resilience of ISNs are quite recent, since the literature has mainly focused on the maximization of the eco-efficiency, i.e., the optimization of the waste flows so as to minimize material and energy consumptions (e.g., Montastruc et al., 2013; Rubio-Castro et al., 2011; Yazan et al., 2016b). Scholarly interest in ISN resilience has increased with the growing awareness that ISNs are extremely vulnerable to perturbations (Chopra and Khanna, 2014; Ruth and Davidsdottir, 2009). A perturbation is defined as any event able to affect the feasibility conditions of IS relationships, which ultimately negatively affects the amount of economic benefits that firms obtain from IS. Since the economic benefit is the main driver pushing firms to form and maintain symbiotic relationships, any perturbation may become particularly critical. Any reduction of the economic benefit arising from the IS may be enough to motivate firms to interrupt the symbiotic flows or, in the worst case, to leave the ISN (Mirata, 2004). This might cause the disruption of the ISN as a result of a domino effect due to the interconnectedness among the firms in the ISN. In fact, a firm that leaves the ISN reduces the economic benefits of the firms with which it exchanged wastes. These in turn can decide to leave the ISN, which may generate a cascade effect that impacts on the rest of the network (Allenby and Fink, 2005; Boons and Spekkink, 2012). Hence, due to close interconnectedness among firms, small perturbations affecting just one or a few firms can have a strongly disruptive impact on the ISN.

To avoid this critical problem, ISNs should be designed to be resilient. Given this importance, understanding resilience of ISNs has become the new imperative of IS research, whose main attention to date, instead, has been concentrated on studying the emergence of ISNs and mechanisms by means of which to make resource exchanges eco-efficient (Yu et al., 2014). Recent studies framing ISNs as CASs (Chertow and Ehrenfeld, 2012) have contributed to drive research towards the investigation of ISN resilience, since it is one of the main properties explaining the dynamics of such systems. However, few studies on the resilience of ISNs have been performed (Meerow and Newell, 2015).

Zhu and Ruth (2013) define ISN resilience as the ability of a system to maintain eco-efficient material and energy flows under disruptions. Similarly, Chopra and Khanna (2014) define resilience as the capability of a system to absorb disruptions, while maintain its structure and function. Zeng et al. (2013) and Li and Shi (2015) conceptualize ISN resilience as the ability to maintain functioning the network elements after disruptions. All these studies adopt a dynamic conceptualization of resilience drawn on the concept of ecological resilience. A way to assess the ability of the ISN to maintain its functions is to measure the impact of a disruptive event on the performance outcomes of the ISN. From a technical point of view, disruptive events include changes in production volumes of outputs produced by ISN firms (due to both endogenous and exogenous causes), natural disasters resulting in unavailability of production plants, changes in production technologies, operation errors. From an economic point of view, disruptive events are changes in the input purchase costs and waste disposal costs. Finally, changes in the normative framework can determine disruptive events such as the impossibility of exchanging specific types of wastes. All these events have negative consequences on the ISN, which can be assessed along three performance dimensions:

- environmental outcomes, e.g., the amount of waste not disposed of in the landfill, the amount of input not purchased from firms outside the network (Park and Behera, 2014; Yazan et al., 2016b);
- economic outcomes, i.e., economic benefits gained by firms involved in symbiotic exchanges (Chertow and Lombardi, 2005);
- structural outcomes, e.g., the number of firms belonging to the network, the number of wastes exchanged, the number of symbiotic relationships in the ISN, the volume of flows exchanged in the ISN (Ashton, 2008; Doménech and Davies, 2011a).

The lower the impact of disruptive events on the performance outcomes, the greater the resilience of the ISN.

Previous studies on resilience of ISNs propose measurements using the metrics of network theory. The ISN is framed as a network composed of nodes linked one with each other: each node corresponds to a firm and each link between two nodes represents a symbiotic relationship among them. Both undirected (Zeng et al., 2013; Zhu and Ruth, 2013) and directed (Chopra and Khanna, 2014; Li and Shi, 2015) network representations were used.

In these studies, resilience is measured concerning two kinds of disruptive events: i) the removal of a given firm from the ISN (complete disruption); and ii) the reduction in the amount of wastes produced and/or required by a given firm (partial disruption) (Chopra and Khanna, 2014; Li and Shi, 2015; Zeng et al., 2013; Zhu and Ruth, 2013).

Two different classes of resilience measurements are distinguished: i) those aimed at quantifying the effect of disruptive events on the overall network performance and ii) those aimed at identifying the key firms within the network, i.e., those firms having the highest impact on the network performance in case of their unavailability caused by a disruptive event. Examples of measurements belonging to the first class are: the remaining number and volume of flows after disruption (Zhu and Ruth, 2013), the number of functioning companies after cascading (Li and Shi, 2015), the number of firms that leave the network (broken nodes) due to unavailability of one company (Zeng et al., 2013). Examples of the second class of measurements are degree centrality, betweenness centrality, and importance of node (Chopra and Khanna, 2014). The most important firms are those whose corresponding nodes are characterized by the highest values of such network measures.

However, in all the previous studies a clear conceptualization of the antecedents of resilience and a theoretical understanding of their role are lacking. This Chapter is devoted to fill this gap, identifying the antecedents of ISN's resilience and designing numerical indicators to assess it.

The Chapter is organized as follows. In Section 5.2, a literature review on the resilience of ecological, complex, and engineering systems is presented. In Section 5.3, a conceptualization of the ISNs resilience is proposed, based on the antecedents previously identified. In Section 5.4, the new ISN resilience measurement index is proposed. In Section 5.5, I test the resilience index on two real ISNs. Finally, discussion and conclusions are presented in Section 5.6.

5.2 Theoretical background: The antecedents of resilience

Resilience is a property of many different systems. It has been investigated in a wide range of fields and disciplines. Here I review the studies concerning the resilience of three types of systems: ecological, complex, and engineering systems (Folke, 2006). This review is not intended to be exhaustive of the studies on the topic (for a recent review see Meerow and Newell, 2015), but is aimed at identifying the main conceptualizations, measures, and antecedents of resilience in those fields that are closely related to IS. Thus, I address the resilience of ecologic systems because IS is considered a sub-field of industrial ecology, the discipline that reproduces in industrial contexts the principles of natural ecosystems (Frosch, 1992; Garner and Keoleian, 1995). Complex systems literature is reviewed, because ISNs are framed as CASs (Chertow and Ehrenfeld, 2012) and resilience is one of the main properties of CASs (Limburg et al., 2002). Finally, since IS relationships are implemented within a network of firms (i.e., an ISN), the concept of network resilience is also investigated in the field of engineering systems.

5.2.1 Ecological literature

Resilience was introduced to the ecological literature by Holling (1973), who stated that "*resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist*" (p. 17). The feature of resilience emerges during the transition of an ecosystem between two equilibrium states. When the first equilibrium state is lost due to a perturbation, the system has to react in order to regain an equilibrium state (Holling, 1973). In this regard, two schools of thought can be distinguished (Holling, 1996). The first sustains that the ecosystem returns to its initial equilibrium state after the perturbation. Accordingly, resilience of an ecosystem is defined as "*how fast the variables return towards their equilibrium following a perturbation*" (Pimm, 1984). Hence, this definition refers to a static conceptualization of resilience. The second school recognizes that ecosystems are complex systems able to evolve over time. Hence, rather than return to its state before the perturbation, such a system may evolve towards a new equilibrium state different from the previous one (Gunderson, 2000). In accordance with this point of view, Walker et al. (2004) defined resilience as "*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*". This definition refers to a dynamic conceptualization of resilience. It is considered as an emergent property related to the self-organized behavior of the ecosystems over time (Gunderson, 2000). This concept of resilience of ecological systems is further developed by Walker et al. (2004), who distinguish four dimensions of resilience: *latitude, resistance, precariousness,* and *panarchy*. *Latitude* is defined as the maximum amount a system can be changed before losing its ability to reorganize within the same state. *Resistance* refers to the facility or difficulty of changing the system, i.e. how resistant it is to change. *Precariousness* is related to how close the current trajectory of the system is to a threshold that, if breached, makes reorganization difficult or impossible. Finally, *panarchy* is related to how the above three components are influenced by the states and the dynamics of the subsystems at scales above and below the scale of interest. Systems characterized by different combinations of these components can have equal ability to maintain their functions under disruptive events.

Two alternative measures are used to assess resilience depending respectively on the two schools of thought previously quoted. According to the former, resilience is measured as the degree to which the system has moved away from the equilibrium state (in time) and how quickly it returns (Ludwig et al., 1997). According to the latter, resilience is measured by the magnitude of disturbance that a system can absorb before redefining its structure by changing the variables and processes that control behavior (Holling, 1973).

The resilience of ecological systems depends on their structural features, in particular, those of diversity and redundancy. As far back as the mid-nineteenth century, Darwin (1859) proposed that a given area is more ecologically stable if it is occupied by a high number of species than if it is occupied by a small number. More recently, two kinds of diversity have been distinguished in the literature and associated with resilience: *functional-group diversity* and *functional-response diversity* (Folke et al., 2004; Walker et al., 2006). A functional group is defined as a group of different organisms with the same functions within the system (for instance pollination, predation or decomposition). The *functional-group diversity* of a system refers to how many functions are performed within the system by the organisms that compose it (Duffy, 2002). However, even within the same functional group, the different organisms can respond differently to environmental changes: the higher the number of different responses, the greater the *functional-response diversity* of the system (Elmqvist et al., 2003). Both these two diversities (the number of different functions performed within the system and the number of different responses to environmental changes) are shown to play a critical role in fostering resilience in ecosystems (Luck et al., 2003).

Redundancy refers to the number of species that perform the same function. High redundancy is able to improve resilience of ecological systems. In fact, even if a species is removed, the ecological function provided by that species may persist within the system, because of the compensation offered by the other species providing the same function (Ehrlich and Ehrlich, 1981). However, the importance to the system of the single ecological functions should be also considered. If a species with a strong ecological function is removed, the consequences for the system may be of greater importance than if a species with minor ecological impact is removed (Walker, 1992). Therefore, in order to guarantee high resilience, it is vital that high redundancy is guaranteed, especially for key functions.

5.2.2 Complex systems literature

> "*In recent years the scientific community has coined the rubric 'complex system' to describe phenomena, structure, aggregates, organisms, or problems that share some common themes: (i) they are inherently complicated or intricate [...]; (ii) they are rarely completely deterministic; (iii) mathematical models of the system are usually complex and involve non-linear, ill-posed, or chaotic behaviour; (iv) the systems are predisposed to unexpected outcomes (so-called emergent behaviour*)" (Foote, 2007, p.410).

Complex systems exhibit important properties such as self-organization, emergence, non-linearity, adaptiveness, and resilience. The latter is conceptualized as the ability of the system to return to the original attractor when perturbed or to evolve towards a new equilibrium state different from the previous one.

Studies on the resilience of CASs span many different contexts: human communities (IPCC, 2012), economic systems (Hallegatte, 2014), financial systems (Anand et al., 2013; Nier et al., 2007), cities and urban areas (Jabareen, 2013; Jansson, 2013; Pelling, 2003), food production and supply systems (Fraser et al., 2006), social and organizational systems (Anderies et al., 2004), and supply chains (Christopher and Peck, 2004; Pettit et al., 2010; Ponis and Koronis, 2012). These studies applied CAS theory to investigate the dynamics of such systems when they are perturbed.

Two different conceptualizations of complex system resilience are recognized in the abovementioned studies: i) the *outcome-based* and ii) the *process-based*. According to the *outcome-based* conceptualization, resilience is defined as

> "*the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions*" (IPCC, 2012, p. 5).

This approach considers resilience in terms of end outcome: accordingly, the system is much more resilient to disturbance, when the likelihood is high of a positive or neutral outcome following a disruptive event. In line with this approach, with specific focus on natural disasters that stress human communities, the English Department for Internal Development (DFID, 2011) provides a measurement scale of resilience, consisting of four possible system outcomes as reaction to a disturbance: i) bounce back better; ii) bounce back; iii) recover but worse than before; and iv) collapse. A system able to achieve a "bounce back" outcome after a disruptive event is more resilient (with respect to the specific disruption) than another system whose outcome after the same disruption is "recover[y] but worse than before" or "collapse". In this sense, resilience depends on the adaptive capacity of such systems, since this feature is related to the capacity to provide answers to changes (Smit and Pilifosova, 2011; Smit and Wandel, 2006). Differently from the previous one, the *process-based* conceptualization focuses on the ability of systems to absorb events, using predetermined coping responses (Cutter et al., 2008). This characteristic is known as the absorptive capacity of the system. In a system with an adequate absorptive capacity, the impact of disruptive events can be attenuated, compared with other systems with a lower absorptive capacity. Hence, the greater the absorptive capacity of the system, the higher its resilience will be.

Both the adaptive capacity and the absorptive capacity have been recognized as two important antecedents of CAS resilience. In particular, a resilient complex system is characterized by high levels of adaptive and absorptive capacity. These are in turn fostered by innovation and learning capabilities (Carpenter et al., 2001; Cumming et al., 2005; Cutter et al., 2008). These studies also recognize that the interconnection among system components is a moderator of the relationship between the adaptive/absorptive capacity and resilience. Interconnections allow for exchanges of information and may create new opportunities fostering the innovation capabilities of the system (Fiksel, 2003). However, excessive levels of interconnection may have a negative impact on the capacity of the system to respond to adverse events (Cumming et al., 2005).

5.2.3 Engineering systems literature

Resilience of engineering systems is defined as the "*ability of a system to sense, recognize, adapt and absorb variations, changes, disturbances, disruptions and surprises*" (Hollnagel et al., 2006, pp. 3-4) or similarly as "*the joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation*" (Ouyang, 2014, p.53). Therefore, resilience of engineering systems has been investigated with reference to a static conceptualization, coherently with the first school of thought of the ecological studies on resilience.

Studies on the resilience of the engineering systems have analyzed transportation infrastructures (Feng and Wang, 2013; Nagurney and Qiang, 2007), electric power grids (Crucitti et al., 2004), and communication networks (Crucitti et al., 2004; Latora and Marchiori, 2005). In these studies, resilience is equated with the vulnerability of the engineering system to disruptive events. In particular, the higher the resilience, the lower the vulnerability of the system will be to disruptive events. Two different types of disruptions are distinguished: external and systemic ones (Madni and Jackson, 2009). The first category includes events not depending on the functioning of its components, such as natural disasters, whereas the second includes losses in function, capability or capacity of one or more components that make up the system.

Network theory is the preferred approach to assess resilience of engineering systems. Each component of the system is modeled as a node and links among nodes simulate the physical connections among the components. Disruption affecting one element of the system is modeled as the unavailability of the correspondent node. System resilience is thus measured in terms of the ability of the network to function when nodes are removed or become unavailable, focusing in particular on the capacity to maintain the efficiency of the function and the constancy of the system (Leveson et al., 2006).

Studies in this field have shown that resilience is strongly related to network topology. High interconnectedness among elements is critical, because a disturbance affecting even one member of the system may result in cascade impacts on the other members (Crucitti et al., 2004). The impact of a single node removal on a network's performance is evaluated, assessing the avalanche effect on the network (Criado et al., 2005; Latora and Marchiori, 2005). Studies also show that the most critical nodes for network vulnerability are the most connected ones. Furthermore, networks with low redundancy in connections are more vulnerable to disruptive events.

Table 5.1 summarizes approaches, measures, and antecedents of resilience in ecological, complex, and engineering systems.

Table 5.1. Resilience in ecological, complex, and engineering systems literature.

	Ecological systems	**Complex systems**	**Engineering systems**
Approaches	Dynamic system theory	Complex adaptive system theory	Network theory
Measures	**Static resilience**: how quickly a system returns to its previous state **Dynamic resilience**: the magnitude of disturbance that a system can absorb before loss its functioning	**End-outcome approach**: outcome after disruption **Process-based approach**: absorptive capacity	Vulnerability to node/link removal
Antecedents	Diversity Redundancy	Adaptive capacity Absorptive capacity	Topology Redundancy

5.3 A novel contribution about industrial symbiosis network resilience

In this study, I frame the ISN as an ecosystem where the firms correspond to the organisms and perform specific functions. These functions correspond to the wastes exchanges among firms (Korhonen et al., 2001; Korhonen and Baumgartner, 2009). Firms involved in the exchange may perform the role of producing the waste or using the waste in place of inputs. In doing so, the ISN generates two main services: i) to create economic benefits for firms (organisms); and ii) to create environmental benefits for the collectivity as a whole (external environment). In concert with previous studies (Chopra and Khanna, 2014; Zhu and Ruth, 2013), the resilience of the ISN depends on the impact that the disruption determines on the functions of the ISN. A low impact means that the ISN is able to preserve the waste exchanges (i.e. ISN's functions) under the disruption, so that it is characterized by high resilience. A high impact indicates that the disruption causes the removal of a high number of waste exchanges, so that the ISN's resilience is low.

As to my frame of the ISN as an ecosystem and borrowing from the studies on resilience of ecological systems, I argue that diversity and redundancy play an important role in affecting ISN's resilience.

Since the diversity of the ecosystem is conceptualized as the number of functions performed, the diversity of the ISN is defined as the number of wastes exchanged among the firms. In that, I differ from previous studies that define ISN diversity as the number of firms and exchanges within the ISN (Zhu and Ruth, 2013) or, equivalently, as the number of nodes in the network (Chopra and Khanna, 2014). Similar to the diversity of an ecosystem, the diversity of the ISN is positively associated with resilience. Compared to the ISNs exchanging a low number of wastes, the same disruptive event is lesser critical in the ISNs characterized by a high number of wastes, since the relative impact of the disruption on the network functions is lower.

However, the diversity of a firm also affects the ISN's resilience. Firm diversity is related to the contribution that the firm provides to the functions of the ISN. Such a contribution depends on the number of wastes exchanged (i.e., the number of functions the firm contributes to perform) and the quantity of wastes exchanged (i.e., the extent of the contribution on a specific function). Since the firm can produce and use the wastes, the diversity of the firm is associated with both the number and the quantity of wastes the firm produces and uses. Firms with high diversity have an important role in the ISN: they are able to act as anchor tenants, since they can link themselves to many other firms (Chertow, 1998; Korhonen, 2001a, 2001b). Making a comparison with ecosystems, such firms correspond to the organisms that have a stronger ecological function for the system and, therefore, play the most important role. The removal of these firms is critical for the ecosystem functioning. Similarly, the firms with high diversity, because are involved in a high number of wastes exchanges (functions) in a great extent (quantity exchanged), are those potentially able to mostly impact the ISN in the case of disruptions. For example, consider the case of two firms leaving the ISN, because of a disruption. The first is the single producer of three wastes, whilst the second contributes with three firms to the production of one waste. The first firm is characterized by higher diversity than the second one. The removal of the first firm is more critical than the removal of the second firm, because it would cause the elimination of three waste exchanges rather than of one waste. Hence, firm diversity negatively affects ISN's resilience.

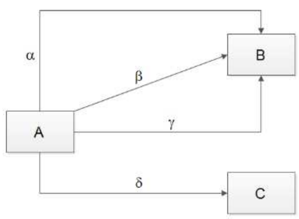
In ecosystems, redundancy refers to the presence of different organisms performing the same function for the system. Because even in smaller ecosystems the number of organisms that perform similar functions is plentiful, redundancy is a natural property of such systems. Framing the ISN as an ecosystem, redundancy is related to the presence of firms producing (requiring) the same wastes. Hence, redundancy is a feature related to each waste produced and used as input. I refer to it as ubiquity of waste. The greater the number of firms producing (using) a given waste, the greater the ubiquity of that waste within the ISN. As in ecosystems, ubiquity does not have a negative meaning in ISNs. On the contrary, the lack of ubiquity is a critical problem for ISNs, because it makes the industrial systems extremely vulnerable towards even small systemic and external disruptions (Chopra and Khanna, 2014). For example, consider the case in which a firm producing a given waste leaves the network. If the waste is not ubiquitous, removing the firm producing that waste is very critical, because the function concerning the exchange of that waste is completely lost. In the case of high ubiquity of the waste, i.e., many other firms in the ISN produce the same waste, the removal of one of the firms producing the waste does not drastically affect the function, which is maintained in the ISN. Therefore, high ubiquity widely contributes to the stabilization of the ISN (Sterr and Ott, 2004). Hence, waste ubiquity is positively associated with ISN resilience.

5.4 Measuring the resilience of industrial symbiosis networks

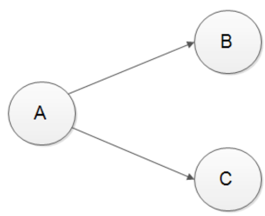
5.4.1 Limitations of network theory metrics

Network-based measurements of resilience present some limitations. I illustrate by means of some examples that they can fail to correctly assess resilience and I show that the reason is related to the difficulty to capture the effect of firm diversity and waste ubiquity on resilience.

Network-based metrics can underestimate the impact of the removal of firms exchanging multiple wastes on ISN's functions. For example, consider an ISN composed of firms A, B, and C and suppose that B uses three different wastes (α, β, γ) produced by A, and C uses only one waste (δ) produced by A. B and C do not exchange any waste one with each other (Figure 5.1a). Thus, all wastes are produced and used by only one firm, i.e. they have ubiquity equal to one. The network theory representation of this ISN is shown in Figure 5.1b. The removal of B and C would cause the same impact on the network, if the impact were measured in terms of links removed and firms remaining. Only one link would be broken (A-B and A-C, respectively) and no other firms would be eliminated from the ISN. Similarly, the removal of B and C would have the same impact if the degree of centrality would be adopted, because both B and C are connected with only one firm. Thus, according to the network-based measurements, firms B and C would be equally critical for the ISN's resilience. However, if I consider that the two firms have a different value of diversity, I can simply ascertain that the removal of firm B from the ISN causes the removal of three different waste flows (three ISN's functions are lost), whereas the removal of firm C causes the removal of only one waste flow (one ISN's function is lost). Hence, the impact of the removal of firm B (having higher diversity) is greater than the removal of C. Hence, B is more critical than C for the ISN's resilience. This situation that cannot be captured by the network-based indices can be easily assessed by an index taking into account firm diversity.



a



b

Figure 5.1. Exemplar symbiotic flows involving firms with different diversity

Moreover, network-based measurements can fail to assess the ISN resilience because of not proper consideration of the ubiquity of waste exchanged. For example, consider the network in Figure 5.2a, where five firms (A, B, C, D, E) exchange three wastes (α, β, γ). Waste α is produced only by firm A, waste β is produced by firms B and E, and waste γ is produced by firm C. Then, all wastes have ubiquity equal to one, except for waste β. Figure 5.2b shows the network theory representation of this ISN. In order to ascertain the impact of the removal of firms A and B, network-based measurements can be used. Based on them, the removal of either firm A or firm B would cause the same impact on the network: one link would be interrupted and no other firm would be eliminated from the network. However, note that if firm A were removed from the ISN, waste α would no longer be exchanged within the network. Thus, the removal of firm A causes the elimination of one ISN's function. On the contrary, if firm B were to leave the ISN, waste β (having higher ubiquity) would continue to be exchanged within the ISN, because it is also produced by firm E. Thus, in such a case no ISN's function would be lost. Hence, the impact of the removal of the firm B should be considered lower than the impact of the removal of firm A. To correctly capture this situation, it is needed to define a proper measure including waste ubiquity.

a b

Figure 5.2. Exemplar network involving firms exchanging wastes with diverse ubiquity.

5.4.2 A new method to measure the resilience of industrial symbiosis networks

To overcome previous limitations and consistently with the theoretical argumentations provided in Section 3, I design a new resilience index. I first define the indices of ISN diversity, firm diversity, and waste ubiquity. Then, I design the impact index to the disruptive event consisting in firm removal, showing that it depends on the three drivers of the ISN resilience. Finally, the resilience index is provided consistent with my conceptualization

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5.4.2.1 The Diversity and Ubiquity indices

I frame the ISN as a network of tri-partite relations among the firms that produce wastes, the wastes exchanged, and the firms that use the wastes as inputs. For a generic ISN composed of f firms exchanging i wastes, two matrices are defined: P and C.

P is an f x w matrix mapping the waste production structure: the generic element Pij denotes the amount of waste j produced by firm i and exchanged within the ISN. Similarly, C is an f x w matrix mapping the waste use structure: the generic element Cij denotes the amount of waste j used by firm i as the result of symbiotic exchanges within the ISN.

The ISN diversity is defined as the number of exchanged wastes among firms.

The firm diversity is defined concerning both the production and waste structures. In the production structure, it is defined as the sum of the ratios between the amount of each waste produced by the firm and the amount of that waste produced within the ISN. Similarly, the firm diversity in the use structure is defined as the sum of the ratios between the amount of each waste used by the firm and the amount of that waste used within the ISN. Both these indices range between zero to *w*: the higher the value, the higher the diversity of the firm.

Each waste exchanged within the ISN is associated with two ubiquity indices: the ubiquity in production and the ubiquity in use. The former is defined as the number of firms that produce that waste whereas the latter as the number of firms that use that waste. The formulas of the diversity and ubiquity indices are shown in Table 5.2.

Table 5.2. Diversity and Ubiquity indices.

	Formula	**Description**
ISN Diversity Index		
Diversity of the ISN	$D_{ISN} = w$	Number of exchanged wastes within the ISN
Firm Diversity Indices		
Diversity of firm i producing wastes	$D_i^P = \sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}}$	Sum of the ratios between the amount of each waste produced by *i* and the amount of that waste produced within the ISN
Diversity of firm i using wastes	$D_i^C = \sum_{j \mid C_{ij}>0} \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}}$	Sum of the ratios between the amount of each waste used by *i* and the amount of that waste used within the ISN
Waste Ubiquity Indices		
Ubiquity of waste j produced	$U_j^P = \sum_{i=1}^{f} p_{ij} \text{ where } \begin{cases} p_{ij} = 1 \text{ if } P_{ij} > 0 \\ p_{ij} = 0 \text{ if } P_{ij} = 0 \end{cases}$	Number of firms producing *j*
Ubiquity of waste j used	$U_j^C = \sum_{i=1}^{f} c_{ij} \text{ where } \begin{cases} c_{ij} = 1 \text{ if } C_{ij} > 0 \\ c_{ij} = 0 \text{ if } C_{ij} = 0 \end{cases}$	Number of firms using *j*

5.4.2.2 The firm resilience index to total disruptions

Consider a disruption event consisting in the removal of a generic firm *i*. For the generic firm *i*, I define the following two impact indices:

$$\iota_i^P = \frac{1}{D_{ISN}} \cdot [(\overrightarrow{d_i^P} \cdot U^{P^{-1}}) \cdot \vec{\alpha}] \tag{5.1}$$

$$\iota_i^C = \frac{1}{D_{ISN}} \cdot [(\overrightarrow{d_i^C} \cdot U^{C^{-1}}) \cdot \vec{\alpha}] \tag{5.2}$$

where the apex *P* stands for the production structure (i.e. the firm in the role of waste producer) and the apex *C* stands for the use structure (i.e. the firm in the role of waste consumer). $\overrightarrow{d_\iota^P}$ and $\overrightarrow{d_\iota^C}$ are the 1x*w* vectors so defined: $\overrightarrow{d_\iota^P} = \left[\frac{P_{i1}}{\sum_{i=1}^{f} P_{i1}} \quad \cdots \quad \frac{P_{iw}}{\sum_{i=1}^{f} P_{iw}}\right]$ and $\overrightarrow{d_\iota^C} = \left[\frac{C_{i1}}{\sum_{i=1}^{f} C_{i1}} \quad \cdots \quad \frac{C_{iw}}{\sum_{i=1}^{f} C_{iw}}\right]$. Hence, these vectors refer to the diversity of firm *i* in waste production structure and waste use structure, respectively.

$U^{P^{-1}}$ and $U^{C^{-1}}$ are the inverse of ubiquity waste matrices, which are defined as diagonal matrices whose elements in the main diagonal correspond to the ubiquity of the wastes produced and used (i.e., $U_{ij}^P = U_j^P \; \forall i = j$ and $U_{ij}^C = U_j^C \; \forall i = j$) , while all the other elements are equal to zero., i.e.

$$U^P = \begin{pmatrix} U_1^P & \ldots & 0 \\ \ldots & \ldots & \ldots \\ 0 & \ldots & U_w^P \end{pmatrix} \qquad U^C = \begin{pmatrix} U_1^C & \ldots & 0 \\ \ldots & \ldots & \ldots \\ 0 & \ldots & U_w^C \end{pmatrix}.$$

$\vec{\alpha}$ is the *w* x1 vector having all elements equal to one, introduced to obtain a scalar value for my indices.

The impact indices so defined capture the extent to which the removal of the firm *i* affects the ISN's functions. This impact depends on ISN diversity, firm diversity, and waste ubiquity, consistently with my theoretical argumentations. First, note that the impact is inversely proportional to the ISN diversity. Second, it increases as firm diversity rises, being the diversity given by $\overrightarrow{d_\iota^P}$ and $\overrightarrow{d_\iota^C}$. The effect of waste ubiquity (U_j^P and U_j^C) is also taken into account. In particular, the higher the ubiquity, the lower the impact due to the firm's removal.

In particular, ι_i^P and ι_i^C range from 0 to 1. ι_i^P = 0 when the firm *i* does not produce any wastes and ι_i^P = 1 when the firm *i* produces all the wastes exchanged within the ISN[4]. Similarly, ι_i^C = 0 when the firm *i* does not use any wastes and ι_i^C = 1 when the firm *i* is the only firm using wastes within the ISN. A high value of ι_i^P corresponds to a firm that produces a high number of wastes with low ubiquity. The removal of such a firm causes a negative impact on the other firms using its wastes, because these firms do not have any alternative internal supplier in the ISN. Similarly, a high value of ι_i^C corresponds to firm that uses a high number of wastes with low ubiquity. The removal of such a firm is detrimental for its waste-supplier firms: firms that produce that waste can experience great difficulty finding another partner in the ISN using it.

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[4] To guarantee that $\frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_\iota^P} \cdot U^{P^{-1}}\right) \cdot \vec{\alpha}\right] = 1$, it is necessary that $\left(\overrightarrow{d_\iota^P} \cdot U^{P^{-1}}\right) \cdot \vec{\alpha} = D_{ISN}$, i.e., that $\sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} = D_{ISN}$. This is possible only if the following two conditions are ensured: i) $\sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} = \sum_{j=1}^{w} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P}$, i.e., that firm *i* produces all kinds of wastes exchanged within the ISN; ii) $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} = 1 \; \forall \; j$. Notice that $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \leq 1$ and $\frac{1}{U_j^P} \leq 1$. In particular, $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} = 1 \Leftrightarrow U_j^P = 1$. Hence, it must happen that firm *i* is the only waste producer within the ISN.

Since a firm's resilience is inversely proportional to its impact on the network due to the firm's removal, the firm resilience index is so defined:

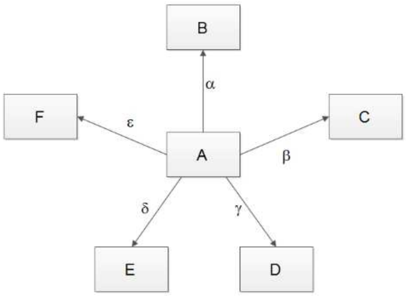
$$\rho_i = 1 - (\iota_i^P + \iota_i^C) \tag{5.3}$$

Because it happens that $\iota_i^P + \iota_i^C \leq 1$[5], it can be stated that $0 \leq \rho_i < 1$. In particular, $\rho_i = 1$ is a theoretical condition that cannot be achieved. In this case, firm *i* should produce and use no waste, which means that it is not involved in the ISN. On the contrary, there are the following three cases in which $\rho_i = 0$:

- firm *i* is the only waste producer within the ISN ($D_i^P = w$ and $U_j^P = 1 \; \forall \; j$): in this case, $\iota_i^P = 1$ and $\iota_i^C = 0$ (see firm A in Figure 5.3a);
- firm *i* is the only waste user within the ISN ($D_i^C = w$ and $U_j^C = 1 \; \forall \; j$): in this case, $\iota_i^P = 0$ and $\iota_i^C = 1$ (see firm A in Figure 5.3b);
- firm *i* produces n wastes with $U_j^P = 1$ and uses $w - n$ wastes with $U_j^C = 1$ (see firm A in Figure 5.3c).

It is noteworthy that that firms with $\rho = 0$ are essential for the survival of their ISNs. In the case of unavailability of such firms due to any disruptive event, the ISN as a whole will disappear.

[5] $\iota_i^P + \iota_i^C$ cannot be higher than 1, because matrices P (waste production structure) and C (waste use structure) take only into account the amount of wastes produced (used) and exchanged within the ISN. Hence, I only consider waste exchanges among different firms, not taking into account the internal re-use of wastes by firms. In fact, it results that $\iota_i^P + \iota_i^C = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_i^P} \cdot U^{P^{-1}}\right) \cdot \vec{\alpha}\right] + \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_i^C} \cdot U^{C^{-1}}\right) \cdot \vec{\alpha}\right] = \frac{1}{D_{ISN}}\left[\sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P}\right] + \frac{1}{D_{ISN}}\left[\sum_{j \mid C_{ij}>0} \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \cdot \frac{1}{U_j^C}\right] = \frac{1}{D_{ISN}}\left[\sum_{j \mid P_{ij}>0} \frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} + \sum_{j \mid C_{ij}>0} \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \cdot \frac{1}{U_j^C}\right] = \frac{1}{D_{ISN}} \sum_{j \mid P_{ij}>0 \; OR \; C_{ij}>0} \left(\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} + \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \cdot \frac{1}{U_j^C}\right)$. In order to guarantee that $\iota_i^P + \iota_i^C \leq 1$, it must be verified that $\sum_{j \mid P_{ij}>0 \; OR \; C_{ij}>0} \left(\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} + \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \cdot \frac{1}{U_j^C}\right) \leq D_{ISN}$, and therefore that $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \cdot \frac{1}{U_j^P} + \frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \cdot \frac{1}{U_j^C} \leq 1 \; \forall j$. Moreover, it results that $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} \leq 1 \; \forall j$ and $\frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} \leq 1 \; \forall j$. In particular, $\frac{P_{ij}}{\sum_{i=1}^{f} P_{ij}} = 1 \Leftrightarrow U_j^P = 1$ and $\frac{C_{ij}}{\sum_{i=1}^{f} C_{ij}} = 1 \Leftrightarrow U_j^C = 1$. However, since I consider only symbiotic exchanges among different firms, even if firm *i* is the only producer of waste *j* ($U_j^P = 1$), it results that $C_{ij} = 0$ and therefore $\iota_i^P + \iota_i^C = 1$. Alternatively, even if firm *i* is the only user of waste *j* ($U_j^C = 1$), it results that $P_{ij} = 0$ and therefore $\iota_i^P + \iota_i^C = 1$.



a

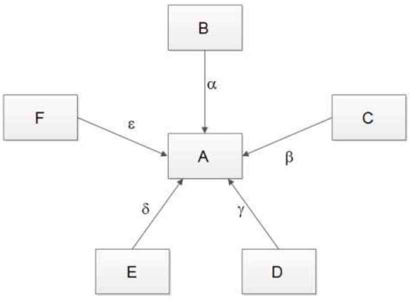
$$\iota_A^P = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_A^P} \cdot U^{P^{-1}}\right) \cdot \vec{\alpha}\right]$$

$$= \frac{1}{5} \cdot \left[\begin{pmatrix}1 & 1 & 1 & 1 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}^{-1}\begin{pmatrix}1\\1\\1\\1\\1\end{pmatrix}\right] = \frac{1}{5} \cdot 5$$

$$= 1$$

$$\iota_A^C = 0$$

$$\rho_A = 1 - (\iota_A^P + \iota_A^C) = 1 - (1 + 0) = 0$$



b

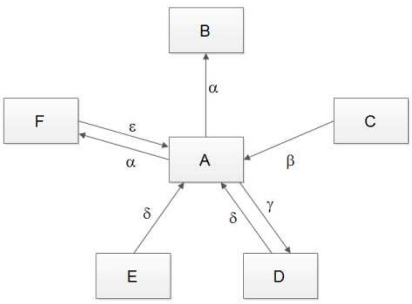
$$\iota_A^P = 0$$

$$\iota_A^C = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_A^C} \cdot U^{C^{-1}}\right) \cdot \vec{\alpha}\right]$$

$$= \frac{1}{5} \cdot \left[\begin{pmatrix}1 & 1 & 1 & 1 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}^{-1}\begin{pmatrix}1\\1\\1\\1\\1\end{pmatrix}\right] = \frac{1}{5} \cdot 5$$

$$= 1$$

$$\rho_A = 1 - (\iota_A^P + \iota_A^C) = 1 - (1 + 0) = 0$$



c

$$D_A^P = \frac{P_{A\alpha}}{P_{A\alpha}} + \frac{P_{A\gamma}}{P_{A\gamma}} = 2$$

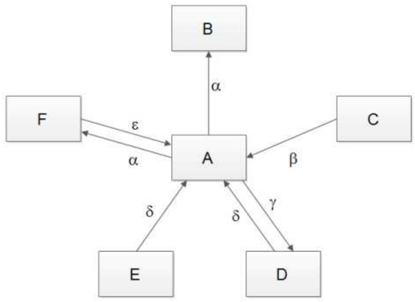
$$\iota_A^P = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_A^P} \cdot U^{P^{-1}}\right) \cdot \vec{\alpha}\right]$$

$$= \frac{1}{5} \cdot \left[\begin{pmatrix}1 & 0 & 1 & 0 & 0\end{pmatrix}\begin{pmatrix}1 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}^{-1}\begin{pmatrix}1\\1\\1\\1\\1\end{pmatrix}\right] = \frac{1}{5} \cdot 2$$

$$= \frac{2}{5}$$

$$D_A^C = \frac{C_{A\beta}}{C_{A\beta}} + \frac{C_{A\delta}}{C_{A\delta}} + \frac{C_{A\varepsilon}}{C_{A\varepsilon}} = 3$$

Figure 5.3. Exemplar networks with $max\{\rho_i\} = 0$.



c

$$\iota_A^C = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_A^C} \cdot {U^C}^{-1}\right) \cdot \vec{\alpha}\right]$$

$$= \frac{1}{5} \cdot \left[\begin{pmatrix} 0 & 1 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \right] = \frac{1}{5} \cdot 3$$

$$= \frac{3}{5}$$

$$\rho_A = 1 - (\iota_A^P + \iota_A^C) = 1 - \left(\frac{2}{5} + \frac{3}{5}\right) = 0$$

Figure 5.3. Exemplar networks with $max\{\rho_i\} = 0$ (continued from previous page).

5.4.2.3 The firm resilience index to partial disruptions

Firm removal is one of the most critical disruptions able to affect ISNs. However, other, less dangerous, disruptive events can occur. Although events such as changes in production levels, equipment faults, and operation errors usually have a lower impact on the network functioning than firm removal, they may occur with higher frequency. Therefore, modeling partial disruption and assessing the ISN resilience to these disruptions is extremely important.

I define a partial disruption as a disruptive event reducing the production capacity of a firm, which in turn determines a decrease of the quantity of the waste it produces or uses.

Thus, I introduce two matrices associated with a partial disruption. Δ^P is the *f*x*w* matrix whose generic element Δ_{ij}^P corresponds to the percent reduction of waste *j* produced by firm *i*. For instance, $\Delta_{ij}^P = 0.4$ means that the amount of waste *j* produced by firm *i* is reduced by 40% due to the partial disruption. Similarly, Δ^C is the *f*x*w* matrix whose generic element Δ_{ij}^C denotes the percent reduction of waste *j* used by firm *i*.

Consider a partial disruption concerning a generic firm *i*. I define the following two impact indices:

$$\iota_{\Delta i}^P = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_i^P} \cdot \widehat{\Delta}_i^P \cdot {U^P}^{-1}\right) \cdot \vec{\alpha}\right] \tag{5.4}$$

$$\iota_{\Delta i}^C = \frac{1}{D_{ISN}} \cdot \left[\left(\overrightarrow{d_i^C} \cdot \widehat{\Delta}_i^C \cdot {U^C}^{-1}\right) \cdot \vec{\alpha}\right] \tag{5.5}$$

where $\widehat{\Delta}_i^P$ and $\widehat{\Delta}_i^C$ are the *w*x*w* matrices whose elements on the principal diagonal are equal to Δ_{ij}^P and Δ_{ij}^C, respectively, and all the other ones are equal to zero.

The resilience of the ISN to the partial disruption of firm i is defined as follows:

$$\rho_{\Delta i} = 1 - (\iota_{\Delta i}^{P} + \iota_{\Delta i}^{C}) \tag{5.6}$$

5.5 Applications

I apply my indices to two real ISNs in order to test how they work. The considered ISNs are located in China (Jinan City) and in Denmark (Kalundborg), respectively. I selected them for several reasons. Both ISNs are of interest. The Kalundborg's ISN is the most famous known and studied example of ISN. For this reason, data on firms, industrial symbiosis relationships, and waste exchanged are available to compute the indices. Furthermore, my results can be compared with those of previous studies. Compared to the Kalundborg's ISN, the Chinese ISN is lesser known but is receiving increasing attention by the literature because involves wastes generated by local community (households) in addition to industrial wastes. This makes the Jinan City's case interesting as well. The two ISNs were also selected because they have different network topologies: a star network for Jinan City and a meshed network for Kalundborg. In this way, I can also show the effect of network topology on ISN's resilience.

For each network, the resilience indices of the ISN firms are computed in the case of total disruption. I also compare my results against diverse measurements: the number of remaining flows after disruption (Zhu and Ruth, 2013), the number of functioning companies after disruption (Li and Shi, 2015; Zeng et al., 2013), degree centrality and betweenness centrality (Chopra and Khanna, 2014).

5.5.1 Jinan City (China)

This first case concerns the ISN located close to the city of Jinan, the capital of Shandong province, the third largest province in China in term of GDP (Dong et al., 2013, 2014). The ISN is made up of six firms and the local community (f=5) and has a star topology. The central node is JIS Corporation, one of the most important enterprises in Jinan: it exchanges eleven different wastes (w=11) with the other firms and the local community. No waste exchange occurs among the other members of the ISN. Figure 5.4 shows the map of firms involved in the symbiotic exchanges and waste flows among them. Each block corresponds to a firm except for the block on the right, which represents the local community.

To compute my indices, I first define the ISN waste production structure (P matrix) and the waste use structure (C matrix) (Table 5.3 and Table 5.4). For each firm and for each waste, the diversity indices and the ubiquity indices are then computed (last row and column of the tables).

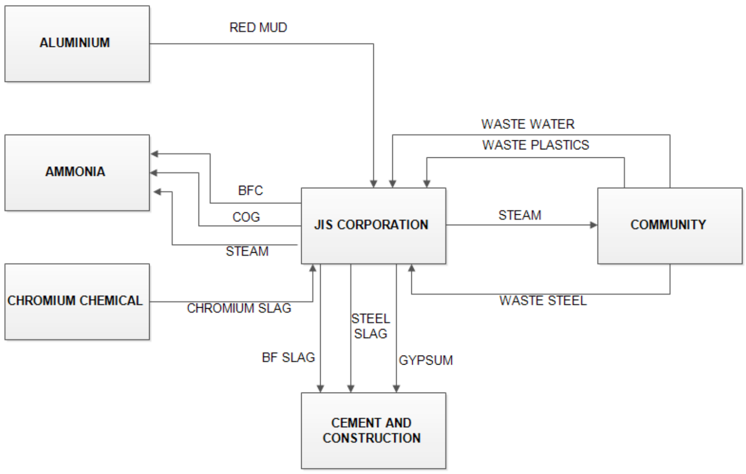


Figure 5.4. Map of the symbiotic exchanges in Jinan City.

This ISN has the following characteristics. On average, each firm produces 1.83 wastes and uses 2 wastes. Firm diversity ranges from 0 to 6 and from 0 to 5 in the production and use structures, respectively. Each waste is on average produced by one firm and used by 1.09 firms. In the production structure, all the 11 wastes have the same ubiquity (1), while in the use structure steam has a ubiquity of 2 and all the other wastes have ubiquity equal to one.

Table 5.3. Waste production structure in Jinan City. Diversity and ubiquity indices.

	BFG [m3]	COG [m3]	STEAM [t]	RED MUD [t]	CHROMIUM SLAG [t]	STEEL SLAG [t]	BF SLAG [t]	GYPSUM [t]	WASTE STEEL [t]	WASTEWATER [t]	WASTE PLASTIC [t]	**FIRM DIVERSITY INDEX (D^P)**
JIS CORPORATION	221810	47160	70900	0	0	1200000	1200000	10000	0	0	0	**6**
COMMUNITY	0	0	0	0	0	0	0	0	1820000	2000000	200000	**3**
CEMENT AND CONSTRUCTION	0	0	0	0	0	0	0	0	0	0	0	**0**
CHROMIUM CHEMICAL	0	0	0	0	120000	0	0	0	0	0	0	**1**
AMMONIA	0	0	0	0	0	0	0	0	0	0	0	**0**
ALUMINUM	0	0	0	1600000	0	0	0	0	0	0	0	**1**
WASTE UBIQUITY INDEX (U^P)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 5.4. Waste use structure in Jinan City. Diversity and ubiquity indices.

	BFG [m3]	COG [m3]	STEAM [t]	RED MUD [t]	CHROMIUM SLAG [t]	STEEL SLAG [t]	BF SLAG [t]	GYPSUM [t]	WASTE STEEL [t]	WASTEWATER [t]	WASTE PLASTIC [t]	**FIRM DIVERSITY INDEX (D^C)**
JIS CORPORATION	0	0	0	1600000	120000	0	0	0	1820000	2000000	200000	**5**
COMMUNITY	0	0	10900	0	0	0	0	0	0	0	0	**0.1537**
CEMENT AND CONSTRUCTION	0	0	0	0	0	1200000	1200000	10000	0	0	0	**3**
CHROMIUM CHEMICAL	0	0	0	0	0	0	0	0	0	0	0	**0**
AMMONIA	221810	47160	60000	0	0	0	0	0	0	0	0	**2.846**
ALUMINUM	0	0	0	0	0	0	0	0	0	0	0	**0**
WASTE UBIQUITY INDEX (U^C)	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 5.5 shows the indices ι_i^P, ι_i^C and ρ_i for all ISN firms. JIS Corporation is characterized by the highest values of both ι_i^P and ι_i^C. Furthermore, it has $\rho = 0$. This means that, in case of disruptive events causing the removal of JIS Corporation from the network, the ISN as a whole will be subjected to disruption. In fact, this case is conceptually analogous to that depicted in Figure 5.3c. Community, Cement and Construction, and Ammonia exhibit a moderate level of resilience (0.7203, 0.7273, and 0.7797, respectively). Chromium Chemical and Aluminum show high resilience indices. Table 5.5 also shows the values of benchmark metrics to assess the ISN's resilience.

Table 5.5. Resilience measurements: Resilience indices, impact, and centrality measures in Jinan.

	RESILIENCE INDEX			IMPACT ON THE NETWORK STRUCTURE		CENTRALITY MEASURES	
	ι_i^P	ι_i^C	$\boldsymbol{\rho_i}$	number of remaining flows after disruption	number of functioning companies after disruption	degree centrality	betweenness centrality
JIS CORPORATION	0.5455	0.4545	**0**	0	0	5	10
COMMUNITY	0.2727	0.0070	**0.7203**	4	5	1	0
CEMENT AND CONSTRUCTION	0.0000	0.2727	**0.7273**	4	5	1	0
AMMONIA	0.0000	0.2203	**0.7797**	4	5	1	0
CHROMIUM CHEMICAL	0.0909	0.0000	**0.9091**	4	5	1	0
ALUMINUM	0.0909	0.0000	**0.9091**	4	5	1	0

A comparison of the resilience index with the other measurements shows that some differences exist. All indices agree that the most critical firm in case of disruption is JIS Corporation. However, as to the disruption of the other firms, my index provides a different result compared to the others. Both the measures concerning the impact on the network and the centrality measures show that the removal of Community, Cement and Construction, Ammonia, Chromium Chemical, and Aluminum results in the same impact on the network. In fact, the removal of one of these firms generates the removal of one link and one firm, with five companies remaining into the ISN. However, the impact is not the same for all these firms. For example, consider Cement and Construction and Aluminum. Even though both exchange wastes just with JIS Corporation, Cement and Construction exchanges three wastes (with ubiquity equal to one), whilst Aluminum one waste (with ubiquity equal to one). Hence, the removal of Cement and Construction impacts three ISN's functions, while the removal of Aluminum influences one function. Therefore, the resilience in the case of removal of Cement and Construction should be lower than the resilience in the case of the removal of Aluminum. While the network-based measures do not capture this, my index shows that the resilience for Cement and Construction is 0.7273 and the resilience for Aluminum is 0.9091, i.e. the resilience to the removal of Cement and Construction is lower than the resilience to the removal of Aluminum.

Moreover, the resilience index is also able to capture that Cement and Construction is more critical than Ammonia for the ISN's resilience, despite both these firms exchange three different wastes with JIS Corporation. In fact, while all wastes exchanged by Cement and Construction have ubiquity equal to one, Ammonia exchanges two wastes with ubiquity equal to one (BFC and COG) but one waste with ubiquity equal to two (steam). This means that whilst the removal of Cement and Construction impacts three functions, the removal of Ammonia eliminates only two functions, since the steam continues to be used by Community. Hence, my resilience proves to perform better than the benchmarks.

5.5.2 Kalundborg (Denmark)

The second case analyzed concerns the ISN in Kalundborg, one of the world's best-known ISNs. The network has been developing since 1961, as the result of an evolutionary process in which a small number of independent by-product exchanges have gradually evolved into a complex web of symbiotic interactions among several firms located within the Kalundborg industrial area and the local municipality (Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Valero et al., 2012). The network involves fourteen firms and the local municipality (f=15) exchanging twelve different wastes among them (w=12). Figure 5.5 shows the map of the waste exchanges within the ISN. Each block corresponds to one firm, except for the "municipality" block, which stands for the local community.

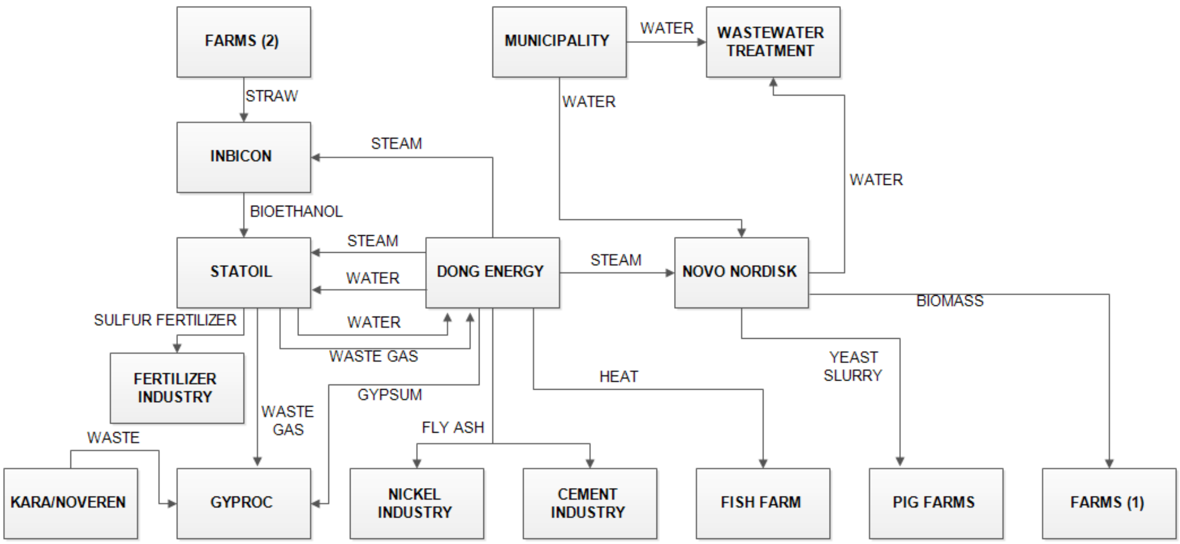


Figure 5.5. Map of the symbiotic exchanges in Kalundborg.

Matrices P and C mapping the waste production and use structures are shown in Table 5.6 and Table 5.7 respectively. They are used to compute both the firm diversity and the waste ubiquity indices (see last row and column in Table 5.6 and Table 5.7). The firms produce on average one different waste and use 1.2 different wastes. In particular, the firm diversity index ranges from 0 to 4.1471 and from 0 to 2.1176 in the production and use structures, respectively. On average, each waste is produced by 1.25 firms and is used by 1.58 firms. In the production structure, the waste ubiquity is 4 for the water and 1 for all the other wastes. In the use structure, water has ubiquity equal to 4, steam equal to 3, waste gas and fly ash 2, and the remaining wastes 1.

Table 5.6. Waste production structure in Kalundborg.

	WATER [m3]	WASTE GAS [t]	BIOMASS [t]	FLY ASH [t]	HEAT [J]	STEAM [J]	YEAST SLURRY [m3]	SULFUR FERTILIZER [t]	GYPSUM [t]	WASTE [t]	STRAW [t]	BIOETHANOL [t]	FIRM DIVERSITY INDEX (D^P)
DONG ENERGY	483000	0	0	300000	3.9E+14	1.5E+15	0	0	80000	0	0	0	**4.1471**
MUNICIPALITY	491000	0	0	0	0	0	0	0	0	0	0	0	**0.1496**
WASTE WATER TREATMENT	0	0	0	0	0	0	0	0	0	0	0	0	**0**
NOVO NORDISK	2300000	0	150000	0	0	0	92000	0	0	0	0	0	**2.7006**
PIG FARMS	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FARMS (1)	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FISH FARM	0	0	0	0	0	0	0	0	0	0	0	0	**0**
CEMENT INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	**0**
NICKEL INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	**0**
KARA/NOVEREN	0	0	0	0	0	0	0	0	0	8000	0	0	**1**
GYPROC	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FERTILIZER INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	**0**
STATOIL	9000	68000	0	0	0	0	0	2800	0	0	0	0	**2.0027**
INBICON	0	0	0	0	0	0	0	0	0	0	0	4300	**1**
FARMS (2)	0	0	0	0	0	0	0	0	0	0	30000	0	**1**
WASTE UBIQUITY INDEX (U^P)	**4**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 5.7. Waste use structure in Kalundborg.

	WATER [m3]	WASTE GAS [t]	BIOMASS [t]	FLY ASH [t]	HEAT [J]	STEAM [J]	YEAST SLURRY [m3]	SULFUR FERTILIZER [t]	GYPSUM [t]	WASTE [t]	STRAW [t]	BIOETHANOL [t]	FIRM DIVERSITY INDEX (D^C)
DONG ENERGY	9000	60000	0	0	0	0	0	0	0	0	0	0	**0.8851**
MUNICIPALITY	0	0	0	0	0	0	0	0	0	0	0	0	**0**
WASTE WATER TREATMENT	2300000	0	0	0	0	0	0	0	0	0	0	0	**0.7006**
NOVO NORDISK	491000	0	0	0	0	5E+14	0	0	0	0	0	0	**0.4829**
PIG FARMS	0	0	0	0	0	0	92000	0	0	0	0	0	**1**
FARMS (1)	0	0	150000	0	0	0	0	0	0	0	0	0	**1**
FISH FARM	0	0	0	0	3.9E+14	0	0	0	0	0	0	0	**1**
CEMENT INDUSTRY	0	0	0	200000	0	0	0	0	0	0	0	0	**0.6667**
NICKEL INDUSTRY	0	0	0	100000	0	0	0	0	0	0	0	0	**0.3333**
KARA/NOVEREN	0	0	0	0	0	0	0	0	0	0	0	0	**0**
GYPROC	0	8000	0	0	0	0	0	0	80000	8000	0	0	**2.1176**
FERTILIZER INDUSTRY	0	0	0	0	0	0	0	2800	0	0	0	0	**1**
STATOIL	483000	0	0	0	0	5E+14	0	0	0	0	0	4300	**1.4805**
INBICON	0	0	0	0	0	5E+14	0	0	0	0	30000	0	**1.3333**
FARMS (2)	0	0	0	0	0	0	0	0	0	0	0	0	**0**
WASTE UBIQUITY INDEX (U^C)	**4**	**2**	**1**	**2**	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 5.8 shows for each firm the resilience indices computed. My resilience index ranges from 0.6268 to 0.9969. Dong Energy, Statoil, and Novo Nordisk are the most critical firms in case of disruptive events. No firm is characterized by $\rho = 0$. Accordingly, no firm is able to drastically affect the survival of the ISN as a whole. This ISN is therefore characterized by a higher resilience than the previous one.

The number of remaining waste flows ranges from 10 to 16 and the number of functioning companies after disruption ranges from 12 to 15. The degree centrality moves from 1 to 7 and the betweenness centrality from 0 to 68.

Table 5.8. Resilience measurements: resilience indices, impact, and centrality measures in Kalundborg.

	RESILIENCE INDEX			IMPACT ON THE NETWORK STRUCTURE		CENTRALITY MEASURES	
	ι_i^P	ι_i^C	$\boldsymbol{\rho_i}$	number of remaining flows after disruption	number of functioning companies after disruption	degree centrality	betwenness centrality
DONG ENERGY	0.3364	0.0368	**0.6268**	10	12	7	68
STATOIL	0.1667	0.0957	**0.7376**	13	14	4	15
NOVO NORDISK	0.1813	0.0124	**0.8064**	12	13	5	45
INBICON	0.0833	0.0926	**0.8241**	14	14	3	13
GYPROC	0.0000	0.1716	**0.8284**	14	14	3	13
PIG FARMS	0.0000	0.0833	**0.9167**	16	15	1	0
FARMS (1)	0.0000	0.0833	**0.9167**	16	15	1	0
FISH FARM	0.0000	0.0833	**0.9167**	16	15	1	0
KARA/NOVEREN	0.0833	0.0000	**0.9167**	16	15	1	0
FERTILIZER INDUSTRY	0.0000	0.0833	**0.9167**	16	15	1	0
FARMS (2)	0.0833	0.0000	**0.9167**	16	15	1	0
CEMENT INDUSTRY	0.0000	0.0278	**0.9722**	16	15	1	0
WASTE WATER TREATMENT	0.0000	0.0146	**0.9854**	15	15	2	0
NICKEL INDUSTRY	0.0000	0.0139	**0.9861**	16	15	1	0
MUNICIPALITY	0.0031	0.0000	**0.9969**	15	15	2	0

Also in this case, my resilience index is better able to capture the impact that the firm removal has on the functions. Novo Nordisk exchanges two wastes with ubiquity equal to one (yeast slurry and biomass) and two wastes with ubiquity higher than one (water, steam), whereas Statoil exchanges three wastes with ubiquity equal to one (bioethanol, sulfur fertilizer, and waste gas) and two wastes with ubiquity higher than one (water, steam). If Novo Nordisk were removed from the ISN, two different wastes would be no more exchanged, with consequently lack of two functions. If Statoil were removed, three different wastes would be no more exchanged and three functions would be lost. Hence, the removal of Statoil is more critical for the ISN than the elimination of Novo Nordisk. My resilience index captures this issue, while both the indices of impact and the centrality measures suggest the opposite, i.e. that Novo Disk is more critical than Statoil.

Consider now the firms Waste Water Treatment (WWT), Municipality, and Fertilizer Industry. WWT and Municipality are linked with two firms, so that they involve two symbiotic relationships, while Fertilizer Industry is only connected with Statoil, corresponding to one symbiotic link. This implies that the removal of the WWT and Municipality is associated with the elimination of two links, while the removal of Fertilizer Industry determines the lack of one link. Thus, according to the indices of impact previously used, the impact for the removal of Fertilizer is lower than for the removal of WWT and Municipality. However, this is not the case because of the different ubiquity of the waste exchanged. If WWT (water user) were removed, the water would continue to be used by Statoil and Dong Energy. Similarly, if Municipality (water producer) were removed, the exchange of water would be maintained, because Statoil, Dong Energy, and Novo Nordisk would continue to produce water. It follows that the "exchange water" function would not be lost, because of the removal of WWT or Municipality. Conversely, Fertilizer Industry exchanges sulfur fertilizer, which is a low-ubiquitous waste. Since such a waste is required only by Fertilizer Industry, the "exchange sulfur fertilizer" function would be lost, if Fertilizer Industry were removed. In such a case, the impact on the function is higher than the previous case. My index correctly shows that Fertilizer Industry is more critical than WWT and Municipality for the ISN resilience.

Finally, consider Farms (2), Cement Industry, and Nickel Industry, which are considered equally critical for ISN's resilience using the indices of impact and centrality measures. Again, this not the case as my resilience index is able to show. All these firms exchange one waste; however, whilst the waste exchanged by Farms (2) (straw) has ubiquity equal to one, the waste exchanged by Cement Industry and Nickel Industry (fly ash) has ubiquity equal to two. Hence, if Farms (2) were eliminated from the ISN, straw would be no more exchanged within the ISN (one function is lost). Conversely, if Cement Industry (Nickel Industry) were eliminated from the ISN, fly ash would continue to be exchanged within the ISN because it will be required by Nickel Industry (Cement Industry). Thus, Farms (2) has a higher impact than Cement Industry and Nickel Industry on the ISN resilience. Note also that the resilience index for Cement Industry is lower than for Nickel Industry. This is due to the different values of firm diversity: despite the firms exchange the same waste, the diversity of Cement Industry is higher than the diversity of Nickel Industry because Cement Industry exchanges higher quantity of fly ash than Nickel Industry. Thus, its removal is more critical than the removal of Nickel Industry. Therefore, the comparison between the results of the resilience index and the other measures previously used confirms that my index is more effective in measuring resilience.

Moreover, let us analyze the case of partial disruptions. Let us assume that Dong Energy reduces its production output of 50%. Such a disruption causes a reduction of 50% in the amount of the wastes produced (water, fly ash, heat, steam, and gypsum) and used (water, waste gas) by Dong Energy. See matrices $\widehat{\Delta}^{P}_{Dong\ Energy}$ and $\widehat{\Delta}^{C}_{Dong\ Energy}$ in Table 5.9 and Table 5.10.

Table 5.9. Matrix $\hat{\Delta}^{P}_{Dong\ Energy}$.

	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	WASTE	STRAW	BIOETHANOL
WATER	0.5	0	0	0	0	0	0	0	0	0	0	0
WASTE GAS	0	0.5	0	0	0	0	0	0	0	0	0	0
BIOMASS	0	0	0	0	0	0	0	0	0	0	0	0
FLY ASH	0	0	0	0.5	0	0	0	0	0	0	0	0
HEAT	0	0	0	0	0.5	0	0	0	0	0	0	0
STEAM	0	0	0	0	0	0.5	0	0	0	0	0	0
YEAST SLURRY	0	0	0	0	0	0	0	0	0	0	0	0
SULFUR FERTILIZER	0	0	0	0	0	0	0	0	0	0	0	0
GYPSUM	0	0	0	0	0	0	0	0	0.5	0	0	0
WASTE	0	0	0	0	0	0	0	0	0	0	0	0
STRAW	0	0	0	0	0	0	0	0	0	0	0	0
BIOETHANOL	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.10. Matrix $\hat{\Delta}^{C}_{Dong\ Energy}$.

	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	WASTE	STRAW	BIOETHANOL
WATER	0.5	0	0	0	0	0	0	0	0	0	0	0
WASTE GAS	0	0.5	0	0	0	0	0	0	0	0	0	0
BIOMASS	0	0	0	0	0	0	0	0	0	0	0	0
FLY ASH	0	0	0	0	0	0	0	0	0	0	0	0
HEAT	0	0	0	0	0	0	0	0	0	0	0	0
STEAM	0	0	0	0	0	0	0	0	0	0	0	0
YEAST SLURRY	0	0	0	0	0	0	0	0	0	0	0	0
SULFUR FERTILIZER	0	0	0	0	0	0	0	0	0	0	0	0
GYPSUM	0	0	0	0	0	0	0	0	0	0	0	0
WASTE	0	0	0	0	0	0	0	0	0	0	0	0
STRAW	0	0	0	0	0	0	0	0	0	0	0	0
BIOETHANOL	0	0	0	0	0	0	0	0	0	0	0	0

Let us consider now that Novo Nordisk reduces its production output of 80%. Such a disruption causes a reduction of 80% in the amount of the wastes produced (water, biomass, and yeast slurry) and used (water, steam) by Novo Nordisk. See matrices $\widehat{\Delta}^{P}_{Novo\ Nordisk}$ and $\widehat{\Delta}^{C}_{Novo\ Nordisk}$ in Table 5.11 and Table 5.12. The impact indices to the partial disruption of Novo Nordisk are $\iota^{P}_{\Delta Novo\ Nordisk} = 0.1367$ and $\iota^{C}_{\Delta Novo\ Nordisk} = 0.01$, respectively. Thus, the resilience index is $\rho_{\Delta Novo\ Nordisk} = 0.8533$. Note that the resilience index to the partial disruption of Novo Nordisk is higher than the resilience index to the partial disruption of Dong Energy. This means that the ISN is more resilient to the reduction of 80% in the production output of Novo Nordisk than to the reduction of 50% in the production output of Dong Energy.

Table 5.11. Matrix $\widehat{\Delta}^{P}_{Novo\ Nordisk}$.

	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	WASTE	STRAW	BIOETHANOL
WATER	0.8	0	0	0	0	0	0	0	0	0	0	0
WASTE GAS	0	0	0	0	0	0	0	0	0	0	0	0
BIOMASS	0	0	0.8	0	0	0	0	0	0	0	0	0
FLY ASH	0	0	0	0	0	0	0	0	0	0	0	0
HEAT	0	0	0	0	0	0	0	0	0	0	0	0
STEAM	0	0	0	0	0	0	0	0	0	0	0	0
YEAST SLURRY	0	0	0	0	0	0	0.8	0	0	0	0	0
SULFUR FERTILIZER	0	0	0	0	0	0	0	0	0	0	0	0
GYPSUM	0	0	0	0	0	0	0	0	0	0	0	0
WASTE	0	0	0	0	0	0	0	0	0	0	0	0
STRAW	0	0	0	0	0	0	0	0	0	0	0	0
BIOETHANOL	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.12. Matrix $\hat{\Delta}^{C}_{Novo\ Nordisk}$.

	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	WASTE	STRAW	BIOETHANOL
WATER	0.8	0	0	0	0	0	0	0	0	0	0	0
WASTE GAS	0	0	0	0	0	0	0	0	0	0	0	0
BIOMASS	0	0	0	0	0	0	0	0	0	0	0	0
FLY ASH	0	0	0	0	0	0	0	0	0	0	0	0
HEAT	0	0	0	0	0	0	0	0	0	0	0	0
STEAM	0	0	0	0	0	0.8	0	0	0	0	0	0
YEAST SLURRY	0	0	0	0	0	0	0	0	0	0	0	0
SULFUR FERTILIZER	0	0	0	0	0	0	0	0	0	0	0	0
GYPSUM	0	0	0	0	0	0	0	0	0	0	0	0
WASTE	0	0	0	0	0	0	0	0	0	0	0	0
STRAW	0	0	0	0	0	0	0	0	0	0	0	0
BIOETHANOL	0	0	0	0	0	0	0	0	0	0	0	0

5.6 Discussion

The two case study analyzed in Section 5.5 were useful not only to test the application of the proposed indices to real analysis, but also to show that network-based measurements of ISN's resilience can fail to correctly assess the ISN resilience to disruptive events consisting in firm removal. In fact, in the case of ISNs exchanging multiple wastes, since these measures do not discriminate among diverse flows of wastes linking same firms, they cannot take completely into account the influence of the diversity of firms and the role of waste ubiquity. Therefore, they lack to correctly assess ISN's resilience. My resilience index proved to be better than the benchmarks in doing this.

My resilience index has additional advantage compared with traditional measurements. Since I recognized that firms having a resilience index equal to zero are very dangerous for the ISN survival in the case of their removal, my resilience index proves very quick in identifying networks with very high vulnerability.

My study confirms and extends the literature on ISN resilience. Framing the ISN as an ecosystem, I analyzed three fundamental drivers of ISN resilience: the diversity of the network, the diversity of individual firms, and the ubiquity of the wastes exchanged. To the best of my knowledge, only two previous studies by Zhu and Ruth (2013) and Chopra and Khanna (2014) consider them, but without providing a clear conceptualization of these variables and without developing a theoretical framework explaining the relationship with resilience. As emerged by comparing the case-study analyses, I can also confirm that network topology affects ISN resilience. In fact, I found that the resilience of Jinan City's ISN showing a star topology is lower than that of Kalundborg's ISN having a meshed structure. I explain this outcome by means of the influence that the network topology plays on firm diversity and waste ubiquity and, as a consequence, on resilience. Consider an ISN with a star topology (like Jinan City or, more in general, like the ISNs depicted in Figure 5.3 where the central firm exchanges wastes with all the other firms, among which no exchanges occur. Due to this network structure, the diversity of the central firm is high (because it exchanges a high number of wastes) while the ubiquity of wastes exchanged is low (just one). According to my conceptualization, these two conditions negatively influence resilience. This result is in line with the previous finding by Zhu and Ruth (2013) who find that ISNs are less resilient in the case of disruptions targeted at highly connected firms. I add that this particular structure leads to the very critical situation, whereby a resilience index equal to zero is reached. This means that the ISN is highly vulnerable. Consider now an ISN presenting a meshed network topology characterized by waste flows spread among firms (like the Kalundborg's ISN). In such networks, since waste flows are spread among firms, it is unlikely that only one firm produces or uses all the wastes exchanged, thereby resulting in high value of diversity. The wastes exchanged have also high ubiquity because they are produced and used by many firms. This in turn positively influences resilience.

Finally, the results of my study contribute to the design of sustainable ISNs. Similarly to Chopra and Khanna (2014), in order to ensure that the network is characterized by high resilience, I suggest designing ISNs with high network diversity and guaranteeing high ubiquity of the wastes exchanged. This means to improve the number of wastes exchanged within the network and to promote the production and the use of the same waste in multiple firms, thereby strengthening the services provided by the ISN. Furthermore, I suggest to devote specific attention to the firms characterized by high diversity so as to reduce the risk of disruptive events involving them. I can also suggest which strategies to follow for increasing the resilience in existing ISNs. Once the most critical firms in the ISN have been identified, the lower resilience index could be increased by improving the number of exchanged wastes within the ISN, and/or the waste ubiquity, i.e. the number of firms producing and using such wastes. Both these strategies can be implemented adding new firms within the ISN.

The study presents some limits. In particular, my index is static even though developed in concert with a dynamic conceptualization of resilience as the ability of the system to maintain its functions under disruptions. Furthermore, it does not take into account the economic value of replaced inputs and not-disposed wastes, as well as the environmental impact due to their production and disposal. New indices built to address these issues are a subject for future research. This could be also devoted to the analysis of further determinants of ISN's resilience, such as firm's adaptive capacity and firm's ability to cope with disruption. This will contribute to develop an overarching conceptualization of ISN resilience. Finally, my index is built on the implicit assumption that the removal of a firm producing a given waste does not automatically cause the removal of the firm using that waste, as other studies did. Since the firm using the waste could purchase the same waste from other firms producing it in the ISN or from firms outside the

ISN, I believe that this assumption is realistic. However, the development of an index capturing this domino effect could be interesting as well and it will be a matter for further research.

Chapter 6. Maximizing sustainability of industrial symbiosis networks: The optimal trade-off between efficiency and resilience

6.1 The mutual relationship between efficiency and resilience in industrial symbiosis networks

In the previous chapters, I focused on investigating properties of efficiency and resilience of ISNs. Both the properties have an important role in enhancing the sustainability of ISNs over a long time.

Efficiency is related to the benefits created by IS exchanges. Since the economic benefits are the first driver moving firms to adopt the symbiotic approach, it is important that ISNs have high level of economic exchange efficiency. Such an efficiency can be enhanced by: i) increasing the technical exchange efficiency; ii) decreasing the redundancy for IS exchanges among firms (see Chapter 4).

Resilience is related to the ability of ISNs to maintain their functions under disruptive events affecting the network. Since ISNs can be highly vulnerable to disruptive events, it is important that ISNs are characterized by high level of resilience. Such a resilience can be enhanced by: i) increasing the ISN diversity; ii) increasing the waste ubiquity (see Chapter 5). In particular, increase the waste ubiquity means increasing the redundancy of symbiotic linkages among firms, i.e., the number of symbiotic partners for each firm of the ISN.

Similarly to ecology, efficiency and resilience are independent properties also in the IS field. In fact, both efficiency and resilience are affected by the redundancy of IS exchanges. Increasing such a redundancy, the efficiency is decreased whilst the resilience is increased. For the sake of clarity, let us consider the ISNs depicted in Figure 6.1. These networks are characterized by the same ISN diversity since only one waste is exchanged among firms. Moreover, let us assume that all the ISNs are characterized by technical exchange efficiency equal to one. This means that all the gross economic benefits generated by these ISNs are equal. ISNs in Figure 6.1 differ from redundancy in symbiotic exchanges: in fact, Firm A exchanges the waste with only one firm (Figure 6.1a), two firms (Figure 6.1b), and three firms (Figure 6.1c).

The ISN in va is the most efficient one from the economic point of view, since transaction costs are minimized. However, such an ISN is characterized by low resilience to perturbations affecting Firm B. In fact, if Firm B leaves the ISN, the ISN will no more be able to perform its function because Firm A will be forced to landfill its waste. Hence, the ISN as a whole will disappear. Accordingly, such an ISN would be low sustainable over the long period.

In order to increase the ISN sustainability over the long period, resilience should be increased. In this regard, the ISN in Figure 6.1b and Figure 6.1c have higher redundancy of symbiotic exchanges, resulting from higher ubiquity for the exchanged wastes. Nevertheless, the higher the redundancy, the higher the transaction costs due to IS will be, and therefore the lower the economic efficiency of the ISN will be. However, too much redundancy may have negative effects, making the IS approach not enough economically convenient for Firm A, which could decide to leave the ISN. Also in this case, the ISN as a whole will disappear. Therefore, such an ISN would be characterized by low level of sustainability over the long period. Similarly to natural ecosystems, a trade-off between efficiency and resilience of ISNs able to maximize the ISN sustainability seems to arise. In this regard, ISNs should have enough efficiency to ensure cooperation among firms. Nevertheless, they should have enough resilience to resist to disruptive events. The trade-off between efficiency and resilience is characterized by an optimal level of redundancy of IS linkages. For top down ISN, the redundancy level can be designed *a priori*; alternatively, for self-organized ISNs the redundancy level results from firms' choices about the number of symbiotic partners with which to interact.

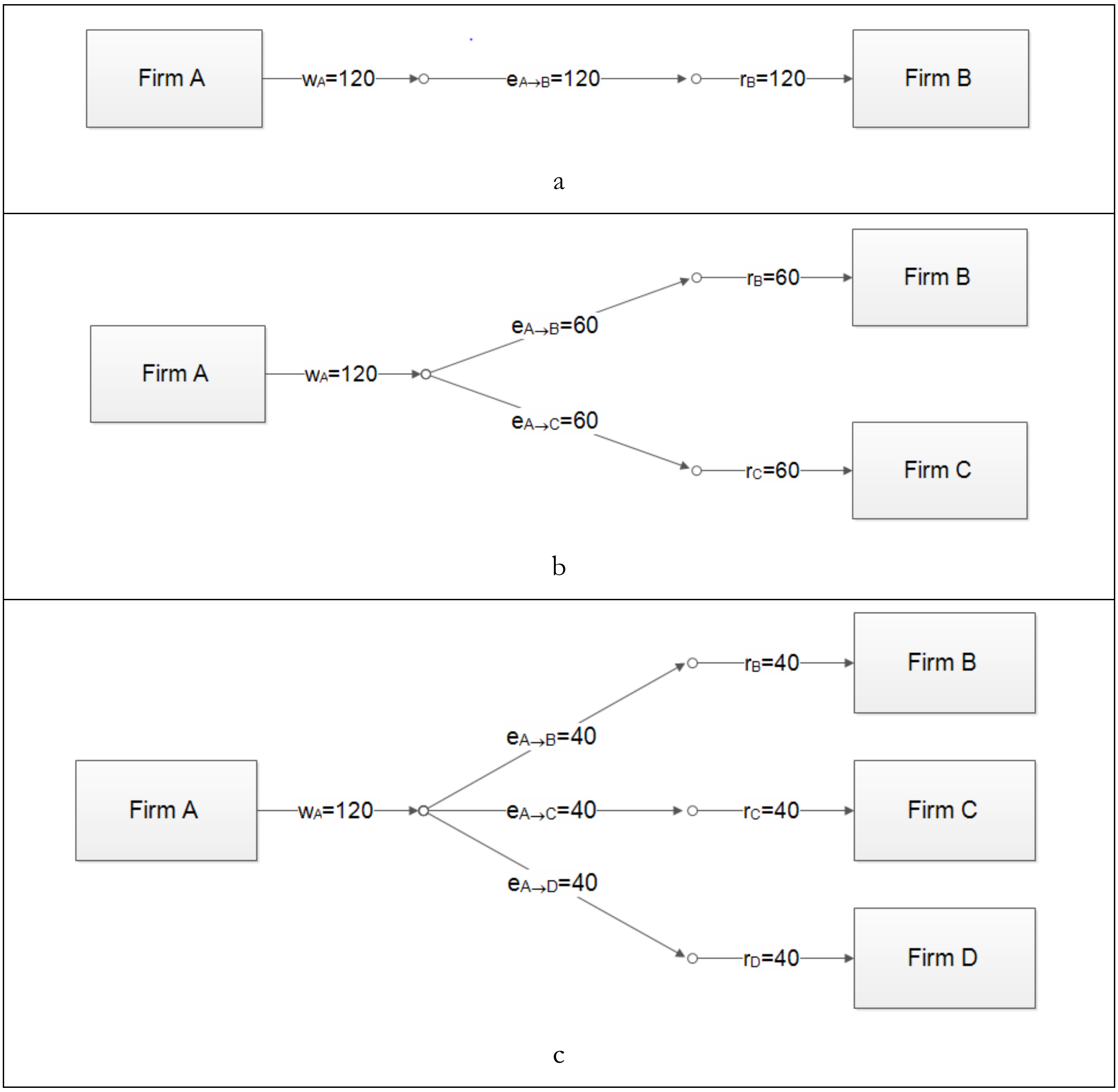


Figure 6.1. ISNs with equal technical exchange efficiency but different levels of redundancy of symbiotic exchanges.

In this Chapter, I investigate the trade-off between efficiency and resilience, able to maximize the ISN sustainability over the long period. I suppose that such a trade-off can be specific for each ISN, depending on two environmental factors: i) the size and frequency of disruptions; and ii) the costs to enhance resilience.

The size and frequency of disruptions depend on the waste market dynamicity, which is related to fluctuations in the amount of both produced wastes and required inputs, therefore affecting the amount of exchanged wastes among firms (see Equation 2.10). In case of one-to-one relationships, high dynamicity makes it difficult to assess in advance the amount of resources available to IS so that quantifying the economic benefit arising from the relationship becomes a hard task (Ehrenfeld and Gertler, 1997). Moreover, high dynamicity is able to create a strong mismatch between produced and required amount of waste, thus reducing the technical exchange efficiency and, as a consequence, the economic exchange efficiency. According to Chapter 3, in such a condition the economic benefits stemming from IS cannot be enough to motivate firms to maintain the symbiotic relationships. I expect that the higher the waste market dynamicity, *ceteris paribus*, the higher the optimal level redundancy will be. Hence, for the ISNs created in these environments, I expect that the trade-off between efficiency and resilience will tend towards resilience.

Costs to enhance resilience are related to transaction costs to manage each symbiotic relationship (Chertow and Ehrenfeld, 2012). For a given firm, the higher the number of partners with which it chooses to cooperate with, the higher the transaction costs it will sustain. Transaction costs erode the economic benefits created by the IS practice. If transaction costs are negligible rather than the economic benefits stemming from IS, the higher redundancy ensures higher resilience to perturbations without significantly decreasing the economic exchange efficiency. In such a case, I argue that firms will be oriented to increase the redundancy of their symbiotic linkages. Alternatively, the higher the weight of transaction costs on the economic benefits created by IS, the lower the redundancy that firm will implement. I expect that the weight of transaction costs can influence the trade-off between efficiency and resilience at ISN level: the higher such a weight, *ceteris paribus*, the more the trade-off will be moved to efficiency. Despite the effects of single parameters on ISNs sustainability may be supposed, I have not any hypothesis about the effect of their mutual interaction.

I explore the optimal trade-off between efficiency and resilience in different scenarios characterized by different levels of waste market dynamicity and transaction costs. Figure 6.2 shows my theoretical framework.

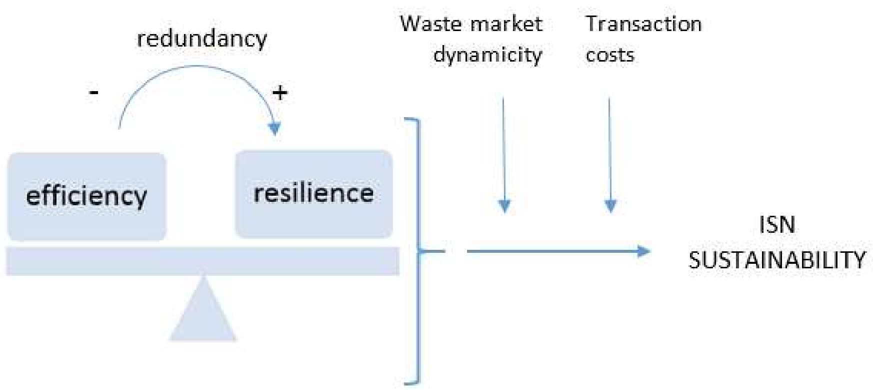


Figure 6.2. Theoretical framework for the trade-off between efficiency and resilience affecting ISN sustainability.

In the field of ecology, it is a common opinion that a system can considered to be sustainable only by observing its behavior *a posteriori* (Costanza, 1999). Accordingly, in order to test the effect of these factors on the sustainability of ISNs, I use an agent-based simulation approach reproducing wastes exchanges within ISNs. In such a way, the sustainability of ISNs over the long periods can be assessed by simulating the ISN dynamics over the long period and measuring the benefits created over all the simulation time.

The rest of the Chapter is organized as follows. Section 6.2 presents the agent-based model adopted to simulate the ISNs. Section 6.3 presents results from simulations. Finally, discussion is provided in Section 6.4.

6.2 Methods

6.2.1 The industrial symbiotic network model: Main features

I consider a given geographic area in which several firms are located. The firms belong to two different unrelated industries (A and B), which are defined as "firm type". Each type is made up by a certain number of firms, n(A) and n(B) respectively, producing a single main product sold on the final market. The production requires a single input purchased from the external supply market and produces a single waste destined to be disposed of in the landfill. Feasible symbiotic relationships exist that involve firms belonging to different types. In particular, each of the n(B) firms belonging to the type B can use as input the waste produced by any of the n(A) firms of the type A. The amount of the waste which can be potentially exchanged at time *t* between the generic firm *i* belonging to type A and the generic firm *j* belonging to type B is computed by using the following equation:

$$e_{i\to j}(t) \leq \min\{W_A \cdot x_i(t); s_{A\to B} \cdot R_B \cdot x_j(t)\} \tag{6.1}$$

where the equality occurs in case of 1-1 relationship, i.e., if firm *i* sends wastes only to firm *j* and firm *j* receives wastes only from firm *i*. However, each firm can interact exchanging wastes with more than one other firm. As the result of the interaction of firms, different ISNs can arise in this geographic area. Redundancy within each ISN is dependent on strategies of single firms about how many partners choose to cooperate with.

6.2.2 The agent-based model of the industrial symbiotic network

Each firm in an ISN is modeled as an agent that has to decide if to cooperate with other agents in exchanging wastes. A fitness function $F_{i\to j}(t)$ ($F_{j\to i}(t)$) is defined that measures the extent to which it is beneficial for the firm *i* (*j*) to exchange wastes with firm *j* (*i*). The higher the fitness value, the higher the willingness of the agent to cooperate with its partner. The fitness functions computed for agents *i* and *j* at period *t* are defined in terms of economic benefits and can be computed by the following equations:

$$F_{i\to j}(t) = \frac{1}{L_{i\to j}(t)+1} \cdot EB_{i\to j}(t) + \left[1 - \frac{1}{L_{i\to j}(t)+1}\right] \cdot F_{i\to j}(t-1) \tag{6.2}$$

$$F_{j\to i}(t) = \frac{1}{L_{i\to j}(t)+1} \cdot EB_{j\to i}(t) + \left[1 - \frac{1}{L_{i\to j}(t)+1}\right] \cdot F_{j\to i}(t-1) \tag{6.3}$$

where $EB_{i\to j}(t)$ and $EB_{j\to i}(t)$ are the economic benefits that *i* and *j*, respectively, gain from the IS relationship rather than their production costs. They can be computed by using the following equations:

$$EB_{i\to j}(t) = \frac{\{udc_i(t) - \lambda_{i\to j}(t) \cdot [utc_{i\to j}(t) \cdot d_{ij} + urc_{i\to j}(t)]\} \cdot e_{i\to j}(t) - cc_{i\to j}(t)}{udc_i(t) \cdot W_A \cdot x_i(t)} \tag{6.4}$$

$$EB_{j\to i}(t) = \frac{\{upc_i(t) \cdot s_{A\to B} - [1 - \lambda_{i\to j}(t)] \cdot [utc_{i\to j}(t) \cdot d_{ij} + urc_{i\to j}(t)]\} \cdot e_{i\to j}(t) - cc_{j\to i}(t)}{upc_j(t) \cdot R_B \cdot x_j(t)} \tag{6.5}$$

where udc_i is the disposal cost of one unit of waste produced by *i*, upc_j is the purchase cost of one unit of input required by *j*, $utc_{i\to j}$ is the cost to transport one unit of waste from *i* to *j*, $urc_{i\to j}$ is the cost to make one unit of waste produced by *i* able to replace input required by *j*, $cc_{i\to j}$ is the transaction cost arising for *i* from cooperation with *j*. For instance, $EB_{i\to j}(t) = 0.15$ means that *i* reduces its production costs by 15% by exchanging wastes with *j*. In general, the economic benefits that firms gain from the IS cooperation depend on: i) the amount of exchanged wastes. In fact, the higher $e_{i\to j}(t)$, the greater the economic benefits will be, *ceteris paribus*; ii) the amount of additional costs stemming from the IS cooperation, *ceteris paribus*; iii) how the economic benefits stemming from the IS cooperation are shared between *i* and *j*. In this regard, $\lambda_{i\to j}$ is representative for the percentage of IS costs sustained by firm *i*. Five different scenarios about monetary flows can occur: i) costs arising from IS are shared between *i* and *j*; ii) firm *i* pays all the costs arising from IS; iii) firm *j* pays all the costs arising from IS ; iv) firm *i* pays firm *j* to dispose its waste, in addition to paying all the costs arising from IS; and v) firm *j* pays firm *i* to purchase its waste, in addition to paying all the costs arising from IS. All these scenarios are depicted in Table 6.1. Moreover, the equations describing all these monetary flows are presented in Table 6.2.

Graphical representation of monetary flows described by these equations is provided in Figure 2.2.

According to Yazan et al. (2012), the firms' willingness to cooperate depends on the economic benefits stemming from the cooperation. Notice that such a willingness is affected by how the economic benefits are shared, as stated in Chapter 3. Accordingly, the higher $\lambda_{i\to j}$, the lower the willingness to cooperate of firm *i* and the higher the willingness to cooperate of firm *j* will be.

Table 6.1. Different cost sharing policy that firm can use in exchanging wastes.

Case	Costs sharing	Monetary flows between firms
$0 < \lambda_{i \to j} < 1$	Costs arising from IS are shared among firms	The waste exchange is for free
$\lambda_{i \to j} = 1$	Firm *i* pays all the costs arising from IS	
$\lambda_{i \to j} = 0$	Firm *j* pays all the costs arising from IS	
$\lambda_{i \to j} > 1$	Firm *i* pays all the costs arising from IS	Firm *i* pays firm *j* to dispose its waste
$\lambda_{i \to j} < 0$	Firm *j* pays all the costs arising from IS	Firm *j* pays firm *i* to purchase its waste

Table 6.2. Equations for monetary flows among firms.

	Firm *i*
[A1] Flows to the firm *j*	$\max\{0, \min[\lambda_{i \to j}(t), 1]\} \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)]$
[A2] Flows to the external environment	$(\max\{0, \lambda_{i \to j}(t)\} - \max\{0, \min[\lambda_{i \to j}(t), 1]\}) \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)] - cc_{i \to j}(t)$
[A3] Total monetary flows	$\max\{0, \lambda_{i \to j}(t)\} \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)] - cc_{i \to j}(t)$
	Firm *j*
[B1] Flows to the firm *i*	$\max\{0, \min[1 - \lambda_{i \to j}(t), 1]\} \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)]$
[B2] Flows to the external environment	$(\max\{0, 1 - \lambda_{i \to j}(t)\} - \max\{0, \min[1 - \lambda_{i \to j}(t), 1]\}) \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)] - cc_{i \to j}(t)$
[B3] Total monetary flows	$\max\{0, 1 - \lambda_{i \to j}(t)\} \cdot [utc_{i \to j}(t) \cdot d_{ij} + urc_{i \to j}(t)] - cc_{i \to j}(t)$

Moreover, the firms' fitness is affected by path dependence. Path dependence theory explains how "history matters", i.e., that in taking decisions actors are influenced by their past experiences (Arthur, 1994). Path dependence one of the key features of a CAS whose evolution is affected by its own history (David, 1994). Path dependence is highly relevant in self-organized IS and taking it into account means to pay attention to the historical accumulations that have resulted from previous operations (Boons and Howard-Grenville, 2009; Chertow, 2007). Path dependence is modeled by the parameter $L_{i \to j}(t)$, which is defined as the number of sequential time periods firms *i* and *j* are involved in an effective resource exchange. Accordingly, $L_{i \to j}(t)$ is equal to zero if agents *i* and *j* did not cooperate at time (*t*-1); when at time *t*, agents *i* and *j* are continuously cooperating for *n* time periods (i.e., the cooperation started at time *t*-*n*), it results $L_{i \to j}(t) = n$. Path dependence is modeled within the fitness function assuming that the longer the time firms *i* and *j* are involved in an effective resource exchange, the lower the importance of the economic benefits at time *t* to determine the extent to which is beneficial for firm *i* to cooperate with firm *j*.

I assume that for firm *i* (*j*) is beneficial to cooperate with firm *j* (*i*) only if the fitness value associated with the symbiotic relationship exceeds a given threshold value T_i (T_j).

6.2.3 The agent-based model dynamics

Each agent might take the following actions:

- evaluating the current relationships in which it is involved;
- renegotiating the current cost-sharing policy
- interrupting an IS relationship;
- seeking a firm with which to establish an IS relationship;
- creating a new IS relationship.

If firms i and j were cooperating at time *t*-1, at time *t* they **evaluate the current relationship** by computing their fitness values (Equations 6.2 and 6.3). If both values are higher than or equal to the respective thresholds, i.e., if $F_{i\rightarrow j}(t) \geq T_i$ and $F_{j\rightarrow i}(t) \geq T_j$, the relationship between *i* and *j* is kept. Each firm only pays enforcement costs as transaction costs[6]. Otherwise, if results that $F_{i\rightarrow j}(t) < T_i$ and $F_{j\rightarrow i}(t) < T_j$ simultaneously, the relationship is interrupted. Finally, if only the fitness value for *i* (*j*) is lower than the threshold value T_i (T_j), firm *i* (*j*) tries to increase its fitness by **renegotiating the current cost-sharing policy**. In particular, firm *i* (*j*) proposes $\lambda'_{i\rightarrow j}(t)$ so that its new fitness $F'_{i\rightarrow j}(t)$ ($F'_{j\rightarrow i}(t)$) would be at least equal to the threshold T_i (T_j). However, such a renegotiating process is affected by bargaining power (BP) of firms. According to Yazan et al. (2012), BP is representative for the dependency of a given firm from its partner. It is defined and measured by the contribution of each firm to the economic benefits of its partner. For the symbiotic relationship between firms *i* and *j*, BP is computed by the following equations:

$$BP_{i\rightarrow j}(t) = \left\{upc_B(t) \cdot s_{A\rightarrow B} - \left[1 - \lambda_{i\rightarrow j}(t)\right] \cdot \left[utc_{i\rightarrow j}(t) \cdot d_{ij} + urc_{i\rightarrow j}(t)\right]\right\} \cdot e_{i\rightarrow j}(t) - cc_{j\rightarrow i}(t) \tag{6.6}$$

$$BP_{j\rightarrow i}(t) = \left\{udc_A(t) - \lambda_{i\rightarrow j}(t) \cdot \left[utc_{i\rightarrow j}(t) \cdot d_{ij} + urc_{i\rightarrow j}(t)\right]\right\} \cdot e_{i\rightarrow j}(t) - cc_{i\rightarrow j}(t) \tag{6.7}$$

The new cost-sharing policy is proposed to firm *j* (*i*) only if firm *i* (*j*) has enough bargaining power to sustain such a proposal, i.e., if $BP_{i\rightarrow j}(t) > BP_{j\rightarrow i}(t)$ ($BP_{j\rightarrow i}(t) > BP_{i\rightarrow j}(t)$). Such a new cost-sharing policy would also affect the new fitness value $F'_{j\rightarrow i}(t)$ ($F'_{i\rightarrow j}(t)$). If firm *j* (*i*) evaluates the new cost sharing policy as a convenient one for itself, i.e., if $F'_{j\rightarrow i}(t) \geq T_j$, it keeps the link, otherwise it **interrupts the symbiotic relationship**. In both cases, firms pay enforcement and negotiation costs. In the case that firm *i* (*j*) has not enough bargaining power to renegotiate the cost-sharing policy, the relationship is interrupted and firms try to **create new symbiotic relationships.** Each firm belonging to type A (B) has a redundancy

[6] This occurs because firms are not involved in neither seeking for the partner nor negotiating the cost-sharing policy.

strategy defining X (Y), i.e., the highest number of partners with which exchanging wastes. Thereby, each firm belonging to type A (B) can simultaneously cooperate with x (y) firms belonging to type B (A), where $0 \leq x \leq X$ ($0 \leq y \leq Y$). When the cooperation between firms i and j is interrupted, firm i **seeks for another firm** k to connect with. Both $F_{i \to k}(t)$ and $F_{k \to i}(t)$ are computed (Equations 6.2 and 6.3), where $\lambda_{i \to j}(t)$ is randomly generate. Let us assume that firm k is currently exchanging wastes with y other firms. Two different situations may happen: i) $y<Y$, hence firm k is available to start a new cooperative relationship; ii) $y=Y$, hence firm k is not available to start a new symbiotic relationship because is currently exchanging wastes with the highest number of firms allowed by its redundancy strategy.

In the former case ($y<Y$), if $F_{i \to k}(t) \geq T_i$ and $F_{k \to i}(t) \geq T_k$ simultaneously, firms establish an IS relationship. If $F_{i \to k}(t) < T_i$ and $F_{k \to i}(t) < T_k$, none of firms is interested to exchange wastes and no cooperation arises. Finally, if $F_{i \to k}(t)$ ($F_{k \to i}(t)$) is lower than the threshold and $F_{k \to i}(t)$ ($F_{i \to k}(t)$) is higher than or equal to the threshold value, firm i (k) proposes to firm k (i) to change the current proposed cost sharing policy, like in the previous case. If firm k (i) evaluates the new cost sharing policy convenient for itself, i.e., if its new fitness value remains over the threshold, the cooperation arises, otherwise no cooperation is launched. In all cases, firms i and k pay search, negotiation, and enforcement costs.

In the latter case ($y=Y$), firm k could decide to interrupt one of its current relationships (in particular, the relationship with the lowest fitness value) and start a new relationship with firm i. Let us assume that firm m is associated with the lowest fitness value. If $F_{k \to i}(t) > (1 + C) \cdot F_{k \to m}(t)$, where $C>0$, firm k interrupts the relationship with firm m to start a new relationship with firm i. Alternatively, if $F_{k \to i}(t) \leq F_{k \to m}(t)$, firm i computes $\lambda'_{i \to k}(t)$ in order that $F'_{k \to i}(t) > (1 + \mathrm{C}) \cdot F_{k \to m}(t)$. In such a case, k interrupts the relationship with m and starts to cooperate with i. In all these cases, firms i and k pay transaction costs in form of search, negotiation, and enforcement costs. Figure 6.3 shows the flow chart describing the agent decision-making process.

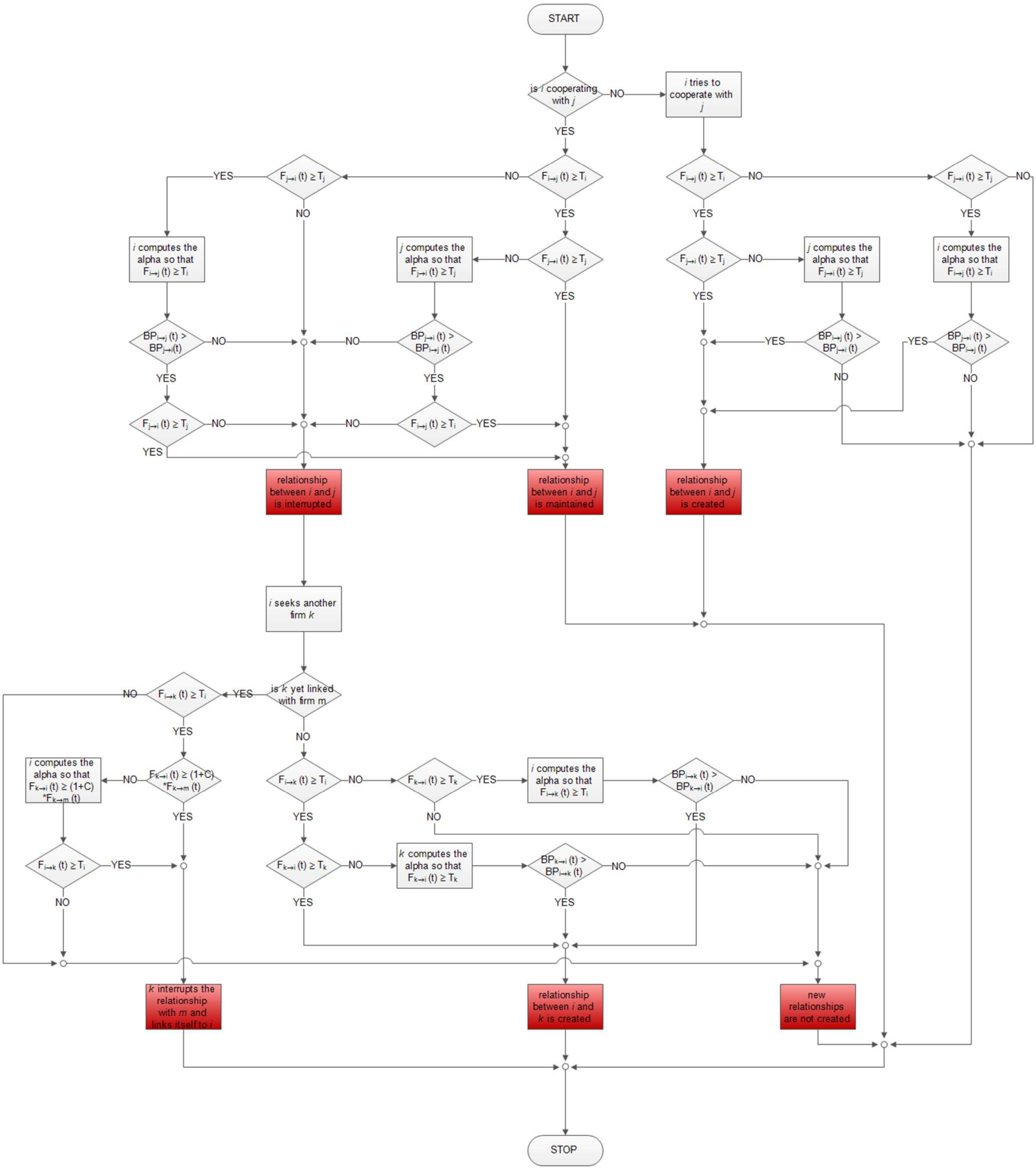


Figure 6.3. Flow chart of the agent decision-making process.

6.2.4 Simulation analysis driven by empirical data

6.2.4.1 Case description

To build my simulation model, I used data referring to a possible case of IS proposed by Yazan et al. (2010). Such a case involves two firms: marble producer and concrete producer. Marble residuals from marble production process could be used by concrete producer as an alternative aggregate in concrete production. Marble residuals are usually not treated but discharged to municipal incinerators or disposed of in the landfill, causing high discharge costs and environmental impacts. Hence, firms producing marble can send marble residuals to firms producing concrete instead of dispose such a waste of in the landfill.

I consider 50 firms producing marble and 50 firms producing concrete randomly spread in a square geographic area with 30 Km side. Euclidean distances among firms are considered. Each firm observed a stochastic final customer demand over time, distributed according to a normal distribution with a given mean and variance. At the beginning of the simulation, each marble producer tries to establish symbiotic relationships with concrete producers. For each established relationship, a formal agreement is created, valid for 3 months. Every three months, firms interact each other, following behavioral rules explained in Section 4.3.

Numerical data on main product demand, raw material requirements, waste produced, marble residuals disposal cost, aggregate purchasing cost, waste transportation cost, and waste treatment cost, obtained from the real case studied, are shown in Table 6.3.

Table 6.3. Numerical data on main products demand, raw material requirements, wastes produced, waste disposal costs, input purchase costs, waste transportation and treatment costs.

	Marble producers	Concrete producers
Final demand (x)	4000 t/year	9800 t/year
Marble residuals ($\boldsymbol{w_A}$)	13252 t/year $\left(W_{AA} = 3.313 \frac{\text{t marble residuals}}{\text{t marble}}\right)$	---
Aggregate needed ($\boldsymbol{r_B}$)	---	13252 t/year $\left(R_{BB} = 1.35 \frac{\text{t aggregate}}{\text{t concrete}}\right)$
Marble residuals disposal costs	$6 \frac{€}{\text{t marble residuals}}$	---
Aggregate purchasing cost	---	$66 \frac{€}{\text{t aggregate}}$
Waste transportation cost	$5 \frac{€}{\text{t marble residuals}\cdot\text{Km}}$	
Waste treatment cost	$0.66 \frac{€}{\text{t marble residuals}}$	

Each firm pays transaction costs for each symbiotic relationship. In particular, these costs have been considered as a fixed percentage *P* of waste disposal costs (for marble producers) and of input purchase cost (for concrete producers). For the generic *i*-th marble producer (belonging to industry A) and the *j*-th concrete producer (belonging to the industry B), it results:

$$cc_{iA\to jB}(t) = P \cdot udc_i(t) \cdot W_A \cdot x_i(t) \tag{6.8}$$

$$cc_{jB\to iA}(t) = P \cdot upc_j(t) \cdot R_B \cdot x_j(t) \tag{6.9}$$

where $0 \leq P \leq 1$. Moreover, I assumed the three components of these costs (search, negotiation, and enforcement costs) are equal. Transaction costs in previous equations refer to the single symbiotic relationship. Notice that these costs are independent on the amount of exchanged waste but they only depend on the amount of produced wastes and required inputs.

6.2.4.2 Sustainability indicators

I defined two indicators to assess the ISN sustainability from both the economic and environmental point of view.

The economic sustainability indicator (ECO_S) is computed as the ratio between the economic benefits created by the IS approach (ECO_B) and the production costs of the involved firms (PC) during all the simulation time:

$$ECO\_S = \frac{\sum_{t=1}^{40} ECO\_B(t)}{\sum_{t=1}^{40} PC(t)} \tag{6.10}$$

where

$$\begin{aligned} ECO\_B(t) = \sum_{i=1}^{50}\sum_{j=1}^{50}\{&[udc_{iA}(t) + upc_{jB}(t) \cdot s_{A\to B} - utc_{iA\to jB}(t) \cdot d_{ij} - urc_{iA\to jB}(t)] \\ &\cdot e_{iA\to jB}(t) - [cc_{iA\to jB}(t) + cc_{jB\to iA}(t)]\} \end{aligned} \tag{6.11}$$

$$PC(t) = \sum_{i=1}^{50} udc_{iA}(t) \cdot w_{iA}(t) + \sum_{j=1}^{50} upc_{jB}(t) \cdot r_{jB}(t) \tag{6.12}$$

ECO_S ranges between 0 and 1 and refers to the percentage reduction in production costs due to IS. For instance, ECO_S=0.6 means that IS has reduced the 60% of the production costs for firms within the ISN. The higher the percentage of production costs reduced by IS, the greater the economic sustainability will be, *ceteris paribus*.

The environmental sustainability measure (ENV_S) is computed as the ratio between the total amount of wastes not disposed of in the landfill and input saved and the total amount of produced wastes and required inputs during all the simulation time:

$$ENV\_S = \frac{\sum_{t=1}^{40}\left[2\sum_{i=1}^{50}\sum_{j=1}^{50} e_{iA\to jB}(t)\right]}{\sum_{t=1}^{40}\left[\sum_{i=1}^{50} w_{iA}(t) + \sum_{j=1}^{50} r_{jB}(t)\right]} \tag{6.13}$$

ENV_S ranges between 0 and 1 and refers to the reduction in material flows from and to the ISN compared to the case of no symbiotic relationships. For instance, ENV_S=0.4 means that IS is reducing waste flows from the ISN and input flows to the ISN by 40% rather than in case of no symbiosis. The higher the percentage of material flows reduced by IS, the greater the environmental sustainability will be, *ceteris paribus*.

6.2.4.3 Simulated scenarios

The simulation scenarios are defined by varying the redundancy (RE) strategy of firms, i.e., the highest number of partners with which a given firm can exchange wastes (values of X and Y). In particular, five different strategies have been considered (thereby, RE ranges from 1 to 5). For instance, when RE=3, each waste producer (user) can send (receive) wastes to (from) no more than 3 waste users (producers). Moreover, each redundancy strategy has been simulated for different levels of waste marked dynamicity and weight of transaction costs on the economic benefits generated. The market dynamicity is modeled through the standard deviation σ of the final customer demand μ compared to the mean value (σ/μ): the higher such a ratio, the higher the dynamicity will be. The weight of transaction costs is modeled by varying P in Equations 6.8 and 6.9. The higher the P, the higher the weight of transaction costs will be. We simulated five values of both waste market dynamicity and weight of transaction costs. Summarizing, the simulation plan consisted of 125 scenarios (5x5x5) (Table 6.4).

Table 6.4. Values of redundancy, market dynamicity, and transaction costs for simulated scenarios.

Variable	Modelling variable	Values
Redundancy (RE)	Highest number of partners with which to cooperate	N = M = 1, 2, 3, 4, 5
Market dynamicity (MD)	Standard deviation of the main product demand	σ/μ = 0.1, 0.2, 0.3, 0.4, 0.5
Transaction costs (TC)	Percentage of transaction cost over waste disposal cost or input purchase cost	P = 0, 0.025, 0.05, 0.075, 0.1

We simulated each scenario for a simulation run of 40 time periods (corresponding to 10 years) and replicate 1000 times so as to give statistical significance results. Moreover, for each scenario, we assumed $T_i = T_j = \frac{0.1}{\mathrm{RE}}\ \forall$ i, j, $s_{A \to B} = 1$, and *C*=0.1.

6.3 Results

6.3.1 Simulation results

Simulation results about ECO_S and ENV_S are shown in Table 6.5 and Table 6.6, respectively. Associated graphical representation is provided in Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 at the end of this Section.

First, we note that in all scenarios MD has a negative effect on both the sustainability indicators. In fact, rising MD from 0.1 to 0.5, *ceteris paribus*, ECO_S decreases between 11.44% and 64.03% and ENV_S decreases between 11.05% and 39.29%, depending on the value of RE and TC. The dynamicity creates a mismatch between demand and supply of waste, which reduces the amount of wastes exchanged among firms, as well as the economic benefits related. This result is consistent with both empirical observations and previous contributions of the literature. Moreover, the transaction costs have a negative effect on both the sustainability indicators *ceteris paribus*, as we expected. In fact, rising TC from 0 to 0.1, *ceteris paribus*, ECO_S decreases between 6.74% and 81.26% and ENV_S decreases between 3.95% and 36.08%, depending on the value of RE and TC. These results confirm the validity of the simulation model.

Let us consider the economic sustainability. First, we note that RE has different effects depending on both TC and MD values. When TC≤0.025, the effect of RE on the economic sustainability is always positive for all values of MD. Hence, the optimal trade-off maximizing the economic sustainability tends towards resilience. In particular, the positive effect of RE is much stronger the higher MD. For example, in case of TC=0 (TC=0.025), if RE rises from 1 to 5, ECO_S grows by 10.14% (8.03%) when MD=0.1 and by 50.55% (41.46%) when MD=0.5. Furthermore, an effect of decreasing returns can be noted. For example, let us consider the scenario with TC=0.025 and MD=0.2: rising RE from 1 to 2, ECO_S grows by 6.48%, but further rising RE from 2 to 3 ECO_S grows by 3.81%. When TC≥0.05, the higher TC the more the optimal trade-off tends towards resilience, *ceteris paribus*. However, such an effect is moderated by MD: in fact, the higher MD, the lower the effect of TC in moving the optimal trade-off to efficiency will be, *ceteris paribus*. For instance, let us consider the scenarios with TC=0.075: ECO_S is maximized by RE=1 when MD=0.1, by RE=2 when 0.2≤MD≤0.4, and finally by RE=3 when MD=0.5. Moreover, it can be highlighted that in some cases RE has always a negative effect on the economic sustainability, thereby the optimal trade-off completely tends towards the efficiency. In fact, when TC≥0.075 and MD=0.1, as well as when TC=0.1 and MD=0.2, ECO_S is maximized for RE=1.

Table 6.5. Economic sustainability measure for each simulated scenario. Green cells denote the highest value for each row.

MARKET DYNAMICITY		TRANSACTION COSTS	REDUNDANCY 1	2	3	4	5
	0,1	0	0.4213	0.4326	0.4466	0.4613	0.4640
		0,025	0.4141	0.4255	0.4355	0.4448	0.4473
		0,05	0.4073	0.4121	0.4077	0.4109	0.3991
		0,075	0.4005	0.3931	0.3698	0.3592	0.3230
		0,1	0.3929	0.3672	0.3303	0.2855	0.2140
	0,2	0	0.3972	0.4237	0.4413	0.4566	0.4594
		0,025	0.3895	0.4147	0.4295	0.4403	0.4409
		0,05	0.3826	0.4008	0.4045	0.4060	0.3925
		0,075	0.3750	0.3836	0.3704	0.3527	0.3165
		0,1	0.3675	0.3584	0.3289	0.2806	0.2038
	0,3	0	0.3716	0.4103	0.4325	0.4490	0.4538
		0,025	0.3646	0.4012	0.4186	0.4315	0.4317
		0,05	0.3562	0.3854	0.3935	0.3951	0.3814
		0,075	0.3467	0.3660	0.3594	0.3401	0.3023
		0,1	0.3371	0.3413	0.3166	0.2650	0.1841
	0,4	0	0.3295	0.3830	0.4113	0.4308	0.4388
		0,025	0.3195	0.3688	0.3925	0.4071	0.4090
		0,05	0.3092	0.3509	0.3640	0.3656	0.3528
		0,075	0.2999	0.3285	0.3258	0.3066	0.2683
		0,1	0.2880	0.3017	0.2780	0.2267	0.1414
	0,5	0	0.2730	0.3410	0.3764	0.3996	0.4109
		0,025	0.2619	0.3220	0.3495	0.3668	0.3712
		0,05	0.2491	0.2996	0.3149	0.3167	0.3064
		0,075	0.2375	0.2710	0.2713	0.2506	0.2137
		0,1	0.2232	0.2408	0.2177	0.1638	0.0770

Table 6.6. Environmental sustainability measure for each simulated scenario. Green cells denote the highest value for each row.

		REDUNDANCY				
MARKET DYNAMICITY	TRANSACTION COSTS	1	2	3	4	5
0,1	0	0.7496	0.8126	0.8419	0.8652	0.8752
0,1	0,025	0.7427	0.7913	0.8118	0.8282	0.8378
0,1	0,05	0.7350	0.7656	0.7779	0.7922	0.7951
0,1	0,075	0.7283	0.7387	0.7446	0.7494	0.7390
0,1	0,1	0.7200	0.7072	0.7125	0.6949	0.6548
0,2	0	0.7053	0.7911	0.8301	0.8560	0.8693
0,2	0,025	0.6965	0.7715	0.8028	0.8232	0.8327
0,2	0,05	0.6891	0.7494	0.7722	0.7874	0.7902
0,2	0,075	0.6798	0.7249	0.7404	0.7448	0.7322
0,2	0,1	0.6722	0.6976	0.7056	0.6896	0.6433
0,3	0	0.6549	0.7597	0.8078	0.8390	0.8553
0,3	0,025	0.6468	0.7413	0.7825	0.8088	0.8201
0,3	0,05	0.6378	0.7208	0.7536	0.7728	0.7768
0,3	0,075	0.6289	0.6972	0.7227	0.7290	0.7149
0,3	0,1	0.6179	0.6719	0.6875	0.6710	0.6211
0,4	0	0.5757	0.7016	0.7627	0.8016	0.8233
0,4	0,025	0.5658	0.6822	0.7370	0.7707	0.7882
0,4	0,05	0.5560	0.6631	0.7089	0.7343	0.7409
0,4	0,075	0.5462	0.6400	0.6771	0.6882	0.6749
0,4	0,1	0.5348	0.6160	0.6395	0.6266	0.5729
0,5	0	0.4817	0.6274	0.7016	0.7499	0.7786
0,5	0,025	0.4709	0.6070	0.6732	0.7157	0.7375
0,5	0,05	0.4595	0.5853	0.6433	0.6737	0.6849
0,5	0,075	0.4494	0.5618	0.6084	0.6216	0.6104
0,5	0,1	0.4371	0.5362	0.5668	0.5533	0.4977

Let us consider the environmental sustainability. It can be noted that the effect of RE is different depending on both MD and TC. When TC≤0.05, the effect of RE on the environmental sustainability is always positive for all levels of MD, i.e., the optimal trade-off maximizing ENV_S tends towards resilience. Moreover, similarly to the economic sustainability, the effect of RE is much higher the greater MD as well as it is characterized by decreasing returns. When TC=0.075, ENV_S is maximized for RE=4. Finally, when TC=0.1, ENV_S is maximized for RE=3, except for the scenario characterized by MD=0.1, where RE=1.

Let us compare ECO_S and ENV_S for each scenario. When TC≤0.025, the scenario with the highest ECO_S (RE=5) corresponds to the scenario with the highest ENV_S. In all other cases, the scenario maximizing ECO_S does not maximize ENV_S simultaneously and *vice versa*. In general, for a given scenario characterized by a given value of TC and MD, RE which maximizes ECO_S is lower than the one maximizing ENV_S. Let us consider for instance the scenario with TC=0.075 and MD=0.3. Figure 6.4 shows both ECO_S and ENV_S values as a function of the redundancy level. Both measures are normalized to one when RE=1. It can be notet that, rising RE from 1 to 2, ENV_S increases by 10.86% whereas ECO_S only by 5.58%. Moreover, rising RE from 2 to 3, ENV_S further increases by 4.05% whereas ECO_S decreases by 1.92%. Hence, nevertheless the additional partner allows to increase the amount of material saved, costs arising from such an additional relationship are higher than the further economic benefits created. In this case, environmental sustainability is maximized in case of RE=4 but economic sustainability is maximized when RE=2.

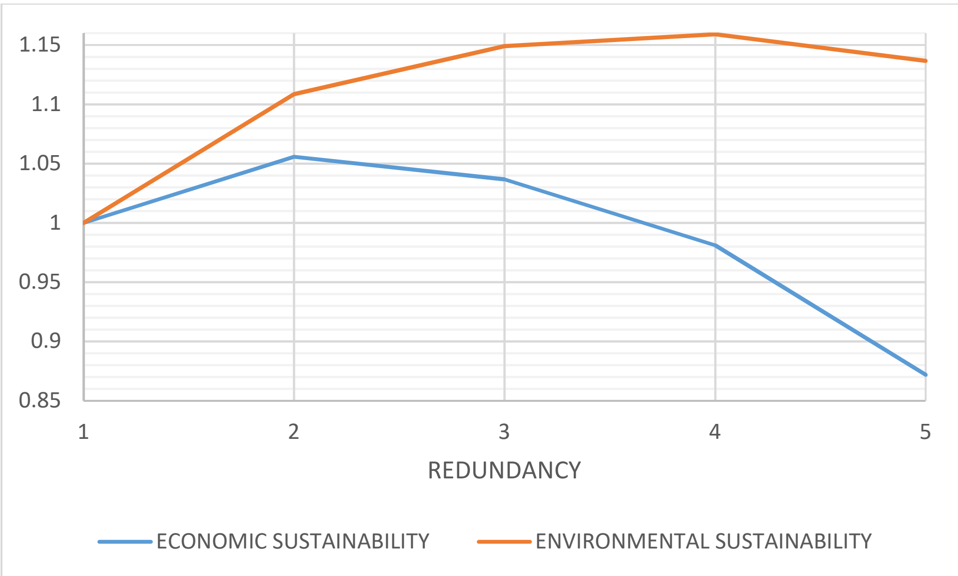


Figure 6.4. Example of different effect of redundancy on sustainability measure and environmental benefits.

Table 6.5 and Table 6.6 show that MD has a negative effect on both the sustainability indicators. However, when TC≤0.025, the negative effect of MD is moderated by RE. Let us consider for instance the scenarios with TC=0: if MD rises from 0.1 to 0.5, ECO_S (ENV_S) decreases by 35.2% (35.74%) when RE=1 whilst it decreases by 11.44% (11.04%) when RE=5.

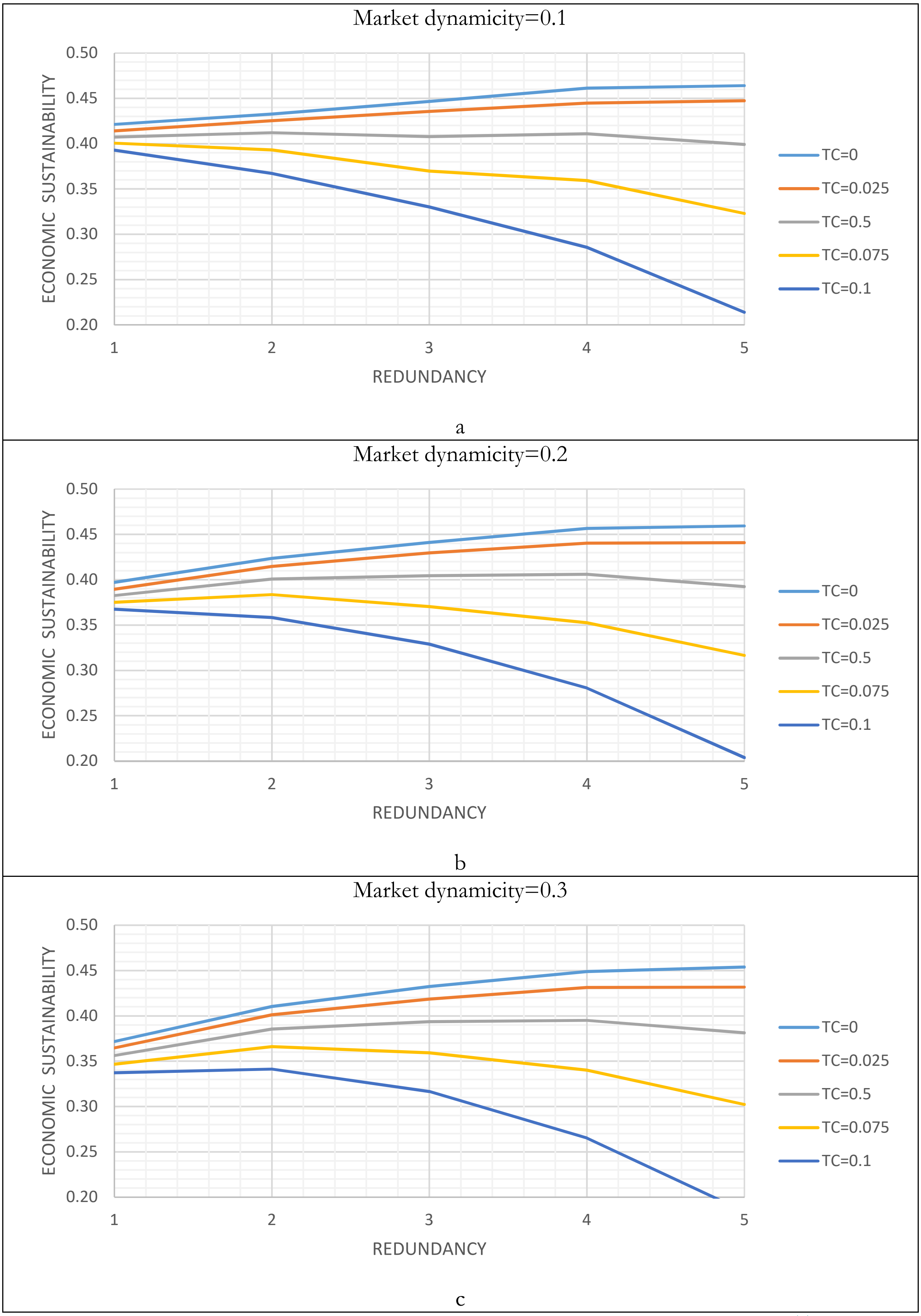
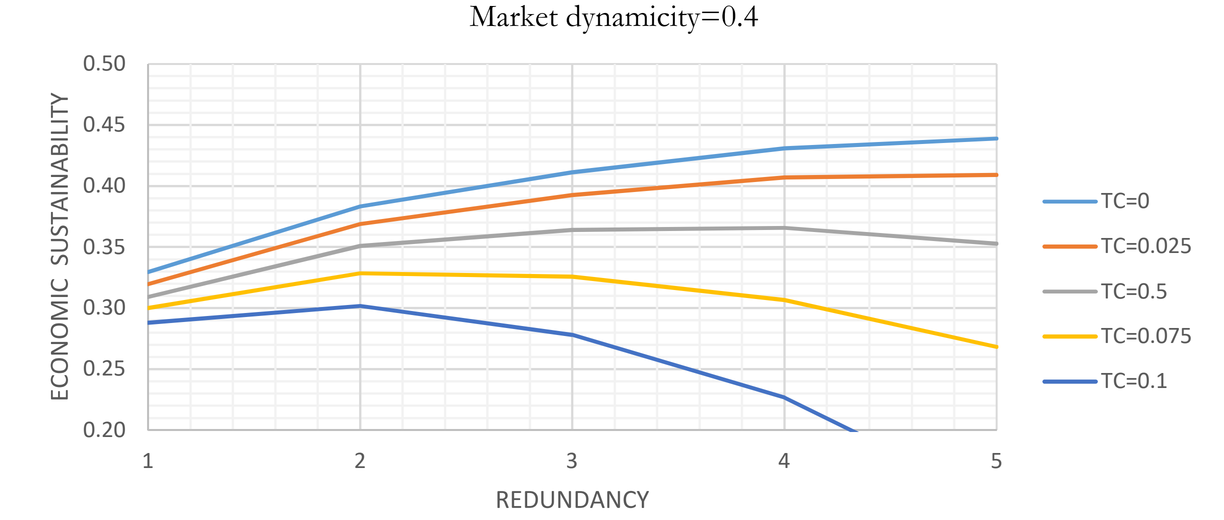


Figure 6.5. Effect of redundancy on the economic sustainability for different levels of transaction costs (TC) in case of different waste market dynamicity.



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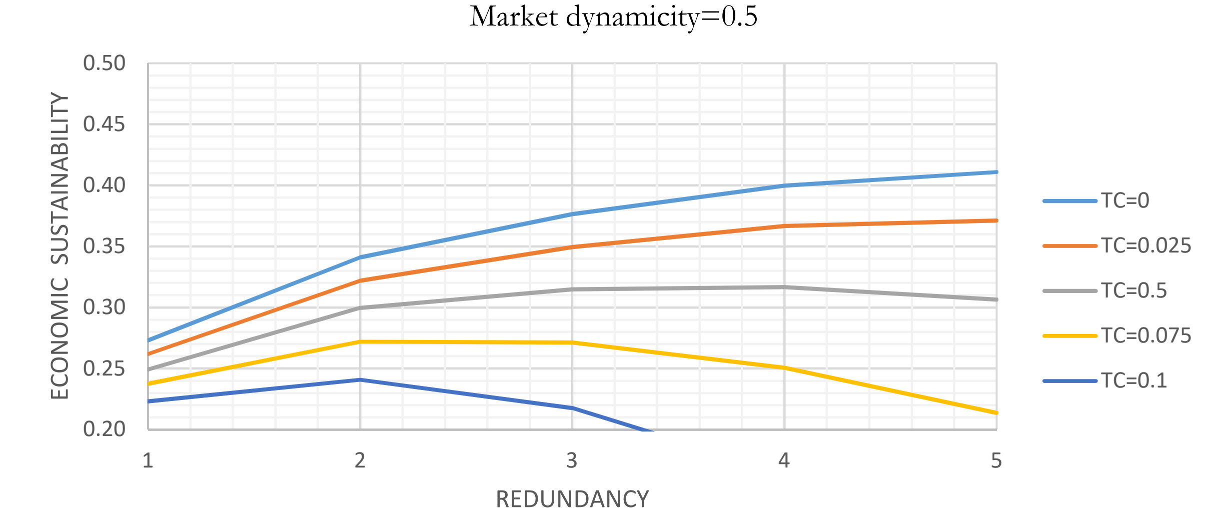

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Figure 6.5. Effect of redundancy on the economic sustainability for different levels of transaction costs (TC) in case of different waste market dynamicity (continued from previous page).

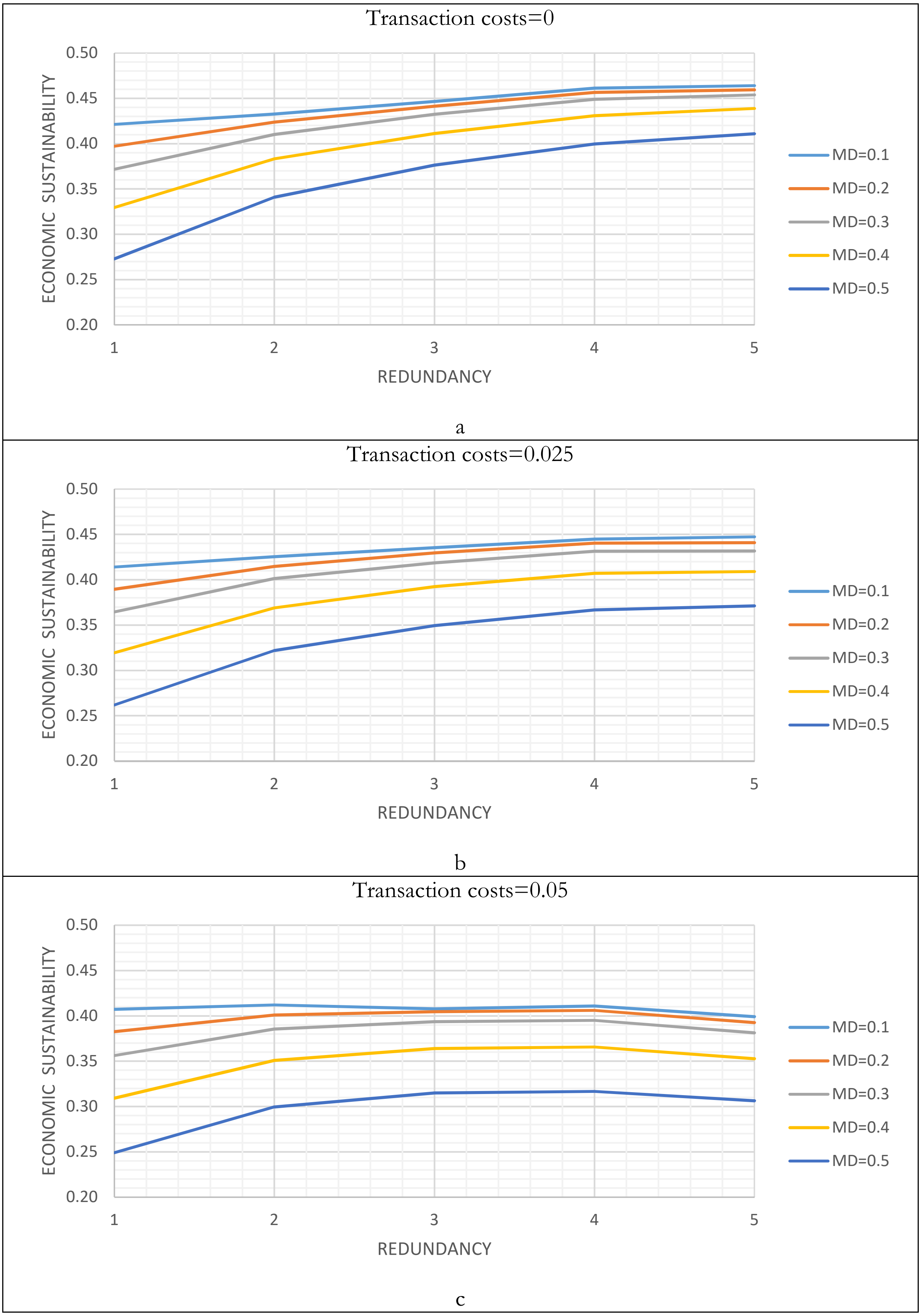
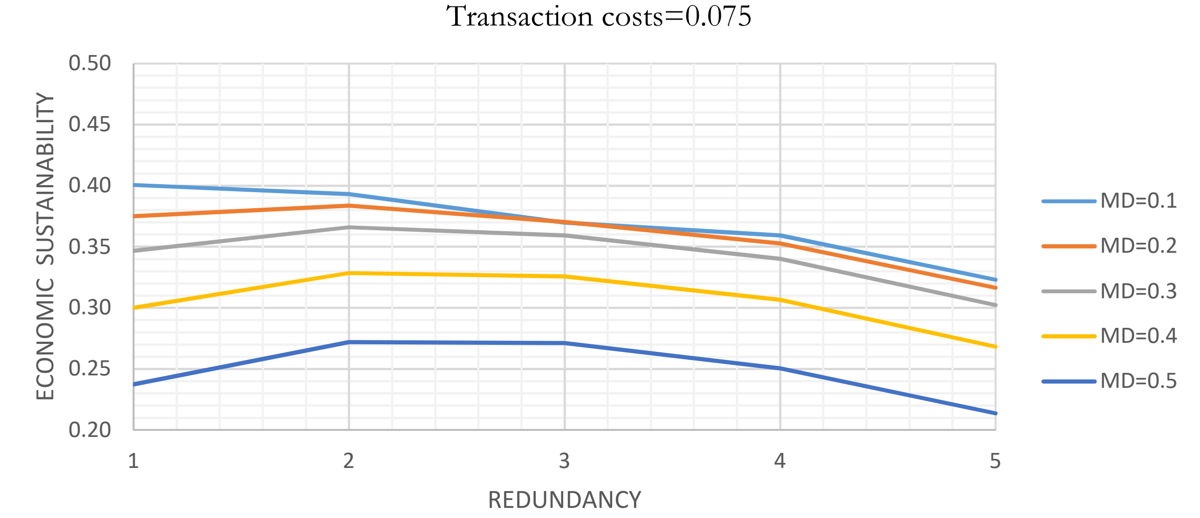


Figure 6.6. Effect of redundancy on the economic sustainability for different levels of market dynamicity (MD) in case of different transaction costs.



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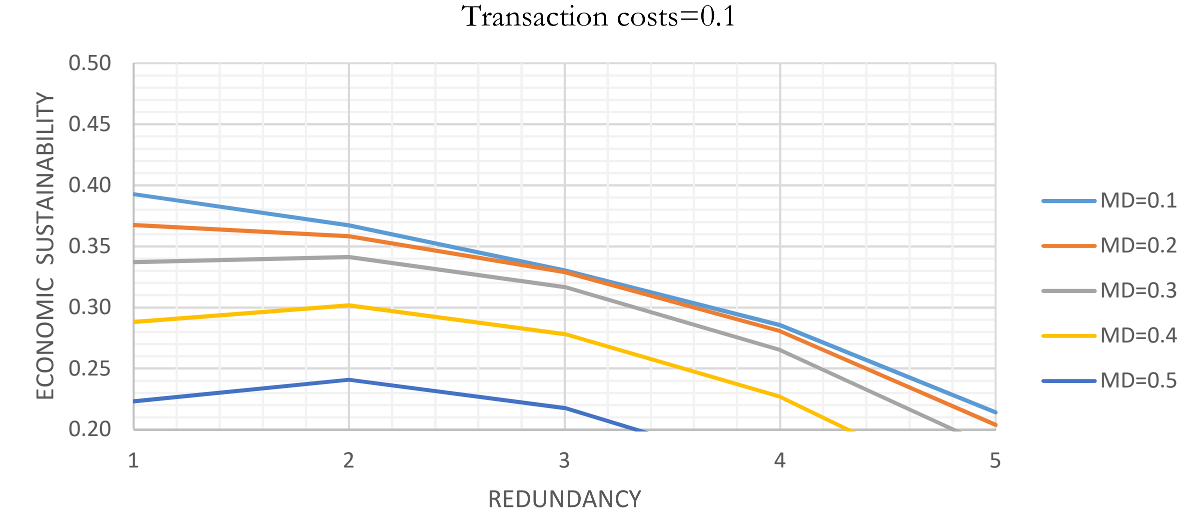


e

Figure 6.6. Effect of redundancy on the economic sustainability for different levels of market dynamicity (MD) in case of different transaction costs (continued from previous page).

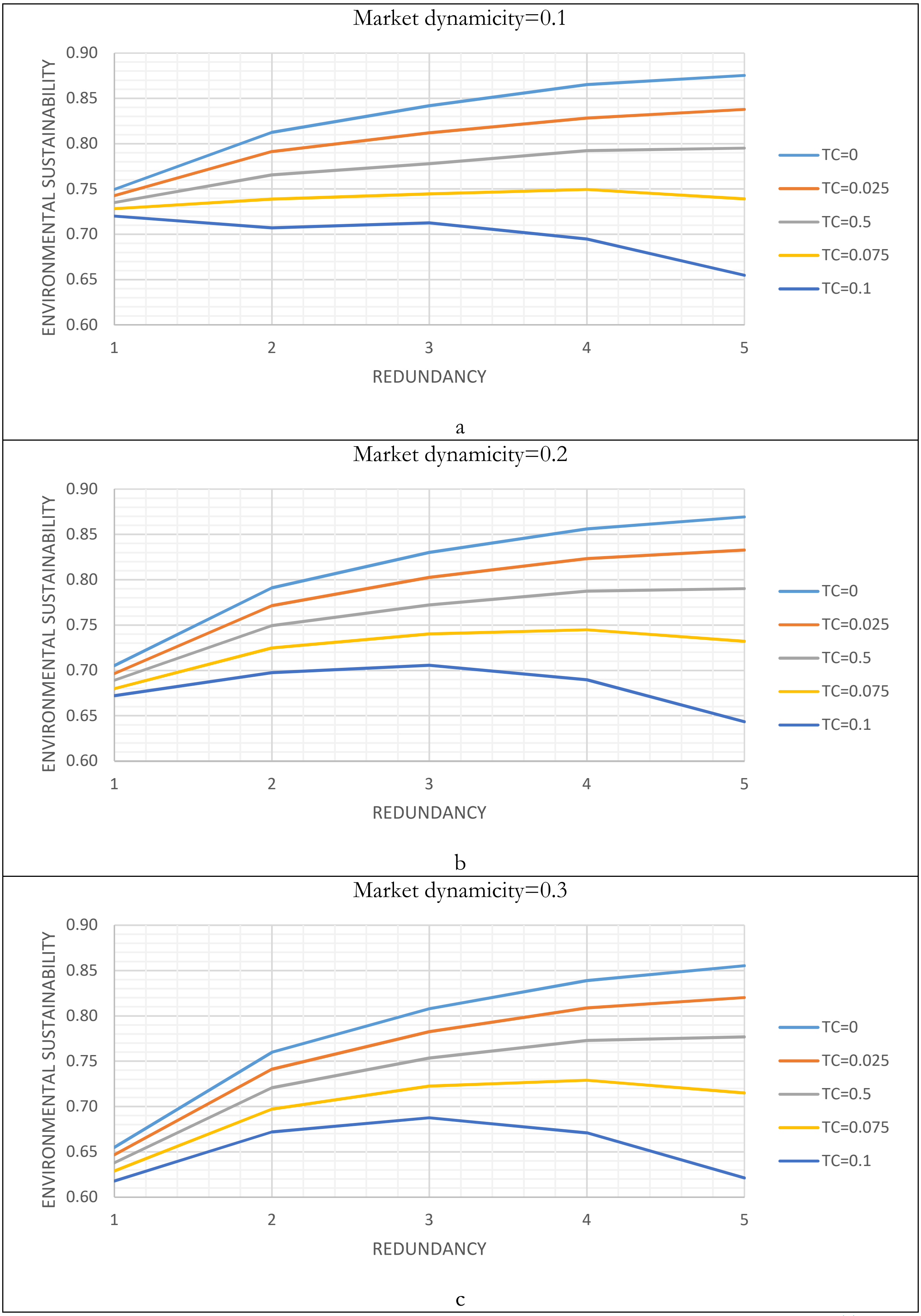
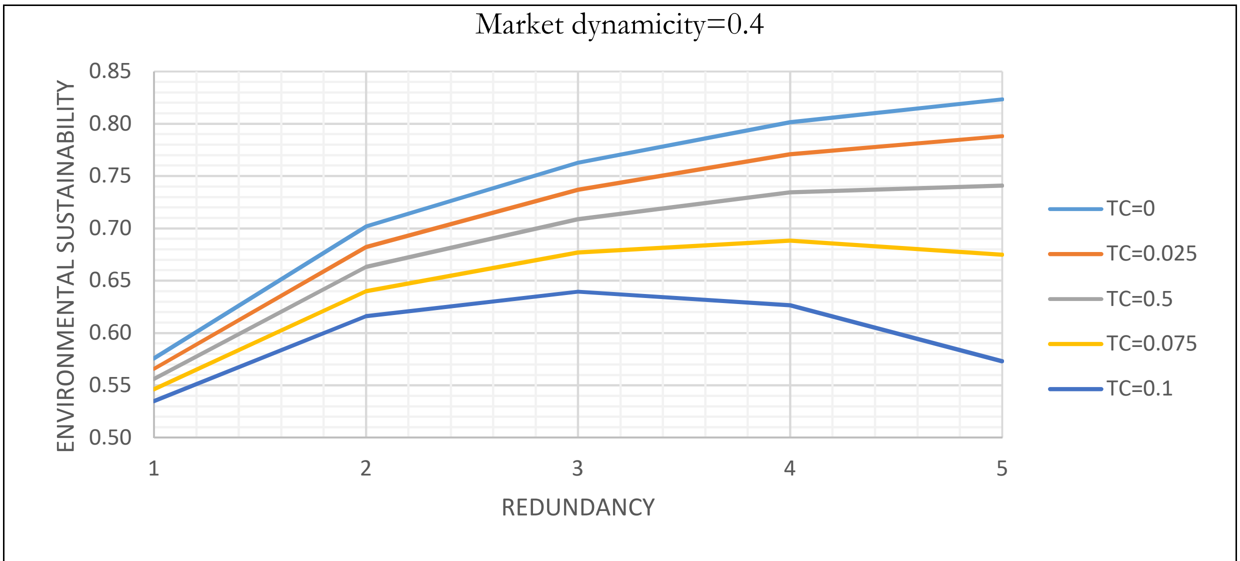


Figure 6.7. Effect of redundancy on the environmental sustainability for different levels of transaction costs (TC) in case of different waste market dynamicity.



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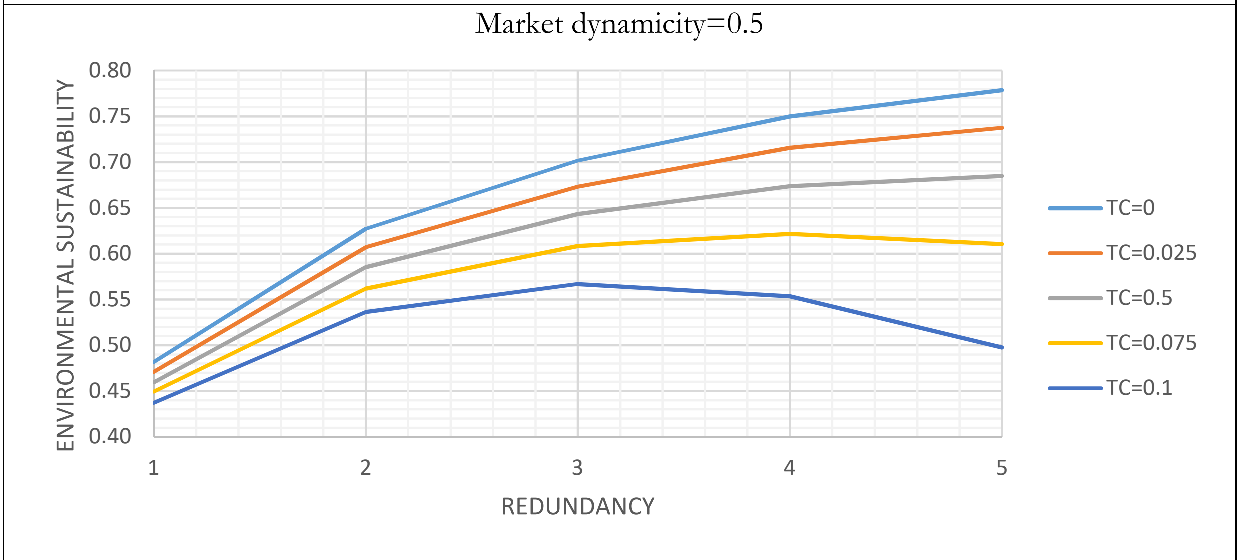
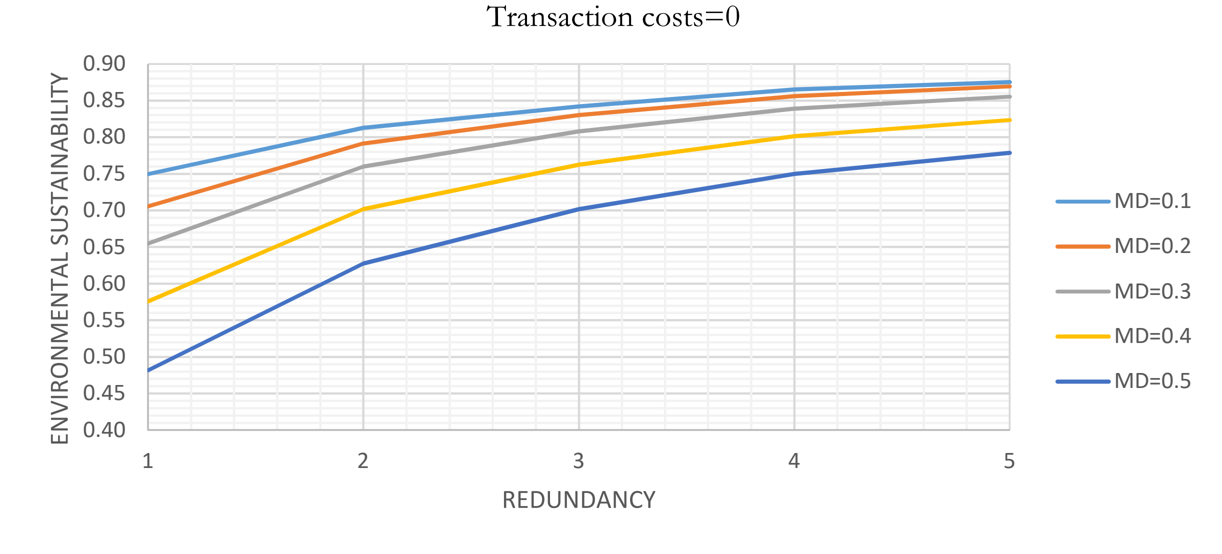
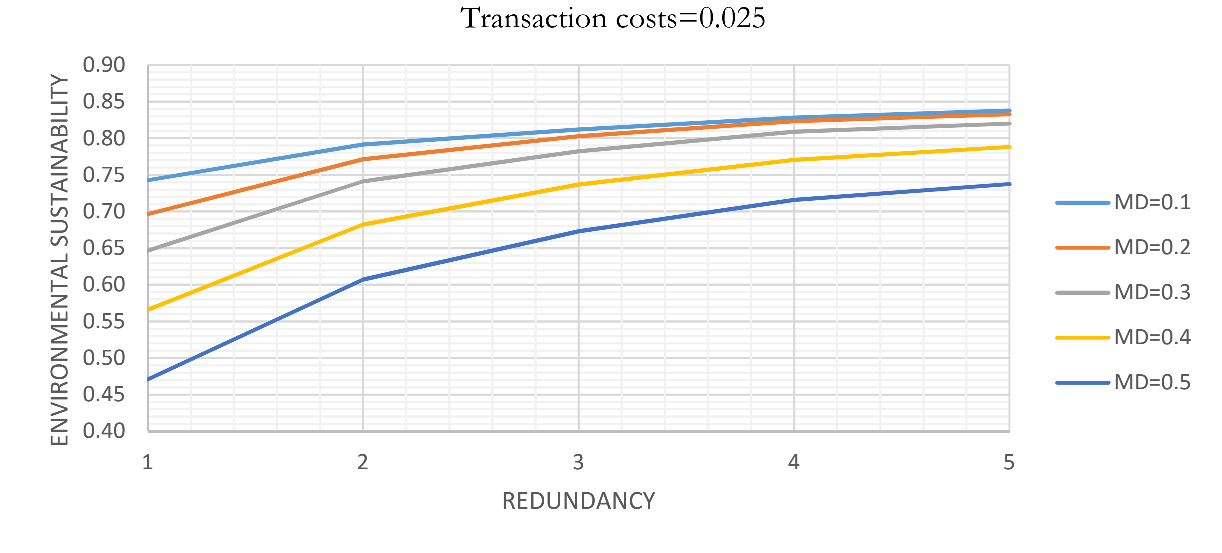


e

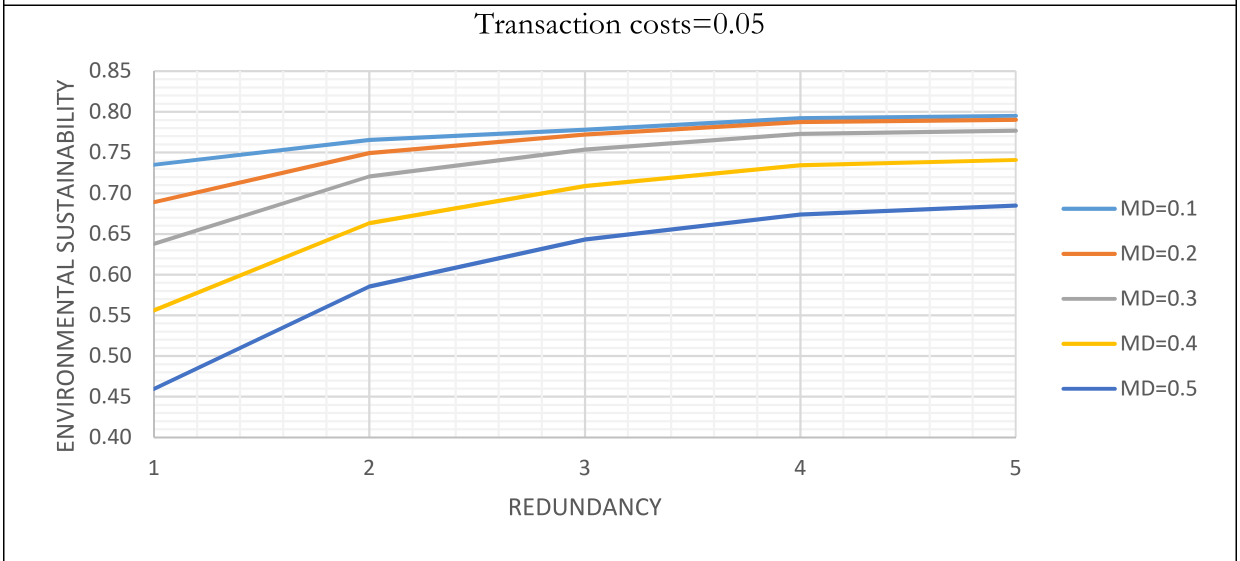
Figure 6.7. Effect of redundancy on the environmental sustainability for different levels of transaction costs (TC) in case of different waste market dynamicity (continued from previous page).



a

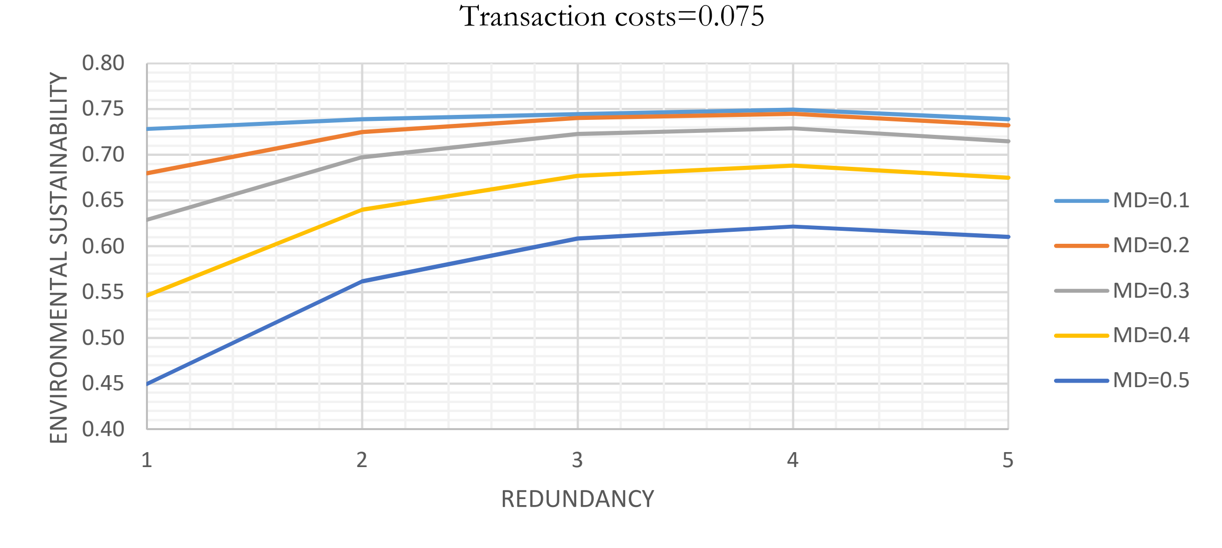


b

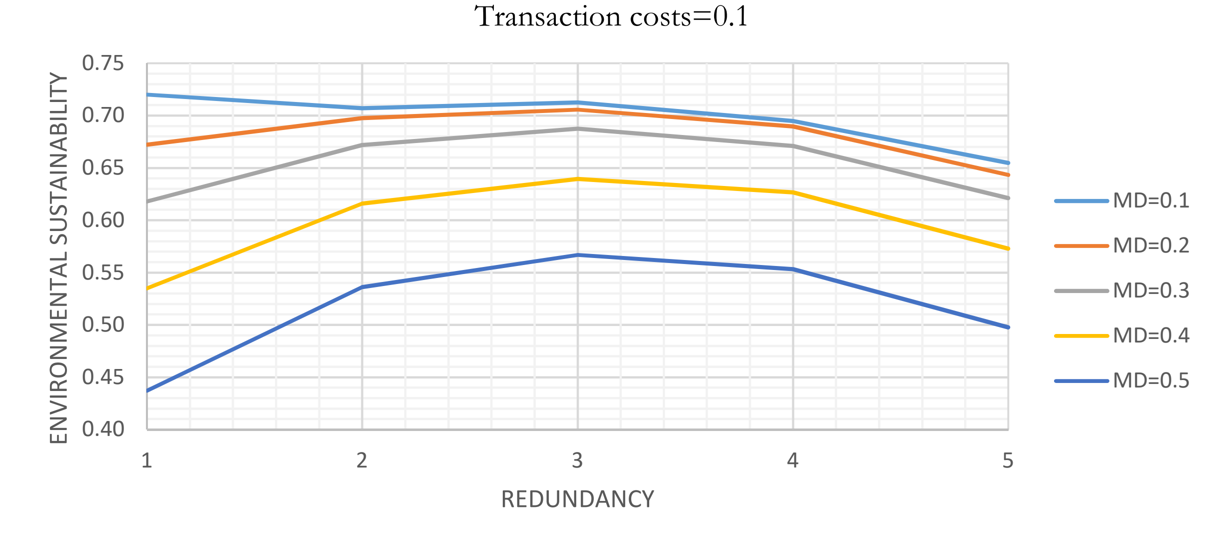


c

Figure 6.8. Effect of redundancy on the environmental sustainability for different levels of market dynamicity (MD) in case of different transaction costs.



d



e

Figure 6.8. Effect of redundancy on the environmental sustainability for different levels of market dynamicity (MD) in case of different transaction costs (continued from previous page).

6.3.2 Model robustness

I tested the robustness of the results simulating a general case where 50 firms producing wastes and 50 firms requiring wastes are located in the same geographic area. On average, each firm producing waste generates 100 tons as well as each firm requiring waste needs to 100 tons of waste.

I simulated the same scenarios described in the previous Section for 40 times, replicating simulations for 1000 times. However, alternatively than the previous Section, geographic and economic parameters are randomly assigned for each simulation, in order to make the model the most generalizable possible. In this regard, it results:

- Maximum distance among firms: 0-100 Km;

- Waste disposal cost: 0-100 €/ton;
- Input purchase cost: 0-100 €/ton;
- Waste transportation cost: 0-30% of waste disposal cost;
- Waste treatment cost: 0-30% of input purchase cost.

Results about ECO_S and ENV_S are depicted in Table 6.7 and Table 6.8, respectively.

Table 6.7. Economic sustainability measure of each simulated scenario. Green cells denote the highest value for each row.

				REDUNDANCY				
				1	2	3	4	5
MARKET DYNAMICITY	0,1	TRANSACTION COSTS	**0**	0.4209	0.4459	0.4626	0.4738	0.4812
			0,025	0.4130	0.4325	0.4416	0.4437	0.4449
			0,05	0.4040	0.4142	0.4078	0.3985	0.3848
			0,075	0.3940	0.3922	0.3645	0.3405	0.2964
			0,1	0.3863	0.3652	0.3170	0.2622	0.1739
	0,2	TRANSACTION COSTS	**0**	0.3968	0.4327	0.4534	0.4662	0.4743
			0,025	0.3873	0.4186	0.4315	0.4363	0.4376
			0,05	0.3799	0.3999	0.3994	0.3920	0.3778
			0,075	0.3698	0.3776	0.3595	0.3317	0.2874
			0,1	0.3608	0.3508	0.3113	0.2517	0.1623
	0,3	TRANSACTION COSTS	**0**	0.3705	0.4172	0.4411	0.4562	0.4659
			0,025	0.3613	0.4015	0.4179	0.4245	0.4271
			0,05	0.3512	0.3824	0.3851	0.3798	0.3634
			0,075	0.3418	0.3586	0.3446	0.3157	0.2706
			0,1	0.3309	0.3308	0.2939	0.2325	0.1408
	0,4	TRANSACTION COSTS	**0**	0.3296	0.3893	0.4199	0.4388	0.4507
			0,025	0.3188	0.3698	0.3922	0.4024	0.4047
			0,05	0.3087	0.3491	0.3568	0.3504	0.3345
			0,075	0.2972	0.3224	0.3114	0.2817	0.2365
			0,1	0.2845	0.2921	0.2570	0.1953	0.1045
	0,5	TRANSACTION COSTS	**0**	0.2846	0.3543	0.3902	0.4133	0.4277
			0,025	0.2691	0.3320	0.3569	0.3691	0.3737
			0,05	0.2564	0.3061	0.3162	0.3101	0.2949
			0,075	0.2409	0.2761	0.2664	0.2373	0.1907
			0,1	0.2289	0.2432	0.2079	0.1470	0.0571

Table 6.8. Environmental sustainability measure for each simulated scenario. Green cells denote the highest value for each row.

MARKET DYNAMICITY			REDUNDANCY				
			1	2	3	4	5
0,1	TRANSACTION COSTS	0	0.7240	0.7830	0.8169	0.8379	0.8511
		0,025	0.7171	0.7655	0.7894	0.8025	0.8100
		0,05	0.7091	0.7448	0.7565	0.7617	0.7589
		0,075	0.7022	0.7213	0.7201	0.7142	0.6926
		0,1	0.6941	0.6949	0.6816	0.6538	0.5977
0,2	TRANSACTION COSTS	0	0.6802	0.7588	0.7999	0.8244	0.8402
		0,025	0.6733	0.7429	0.7742	0.7915	0.8002
		0,05	0.6673	0.7223	0.7434	0.7505	0.7498
		0,075	0.6571	0.7002	0.7091	0.7015	0.6799
		0,1	0.6492	0.6743	0.6702	0.6410	0.5854
0,3	TRANSACTION COSTS	0	0.6306	0.7279	0.7751	0.8041	0.8222
		0,025	0.6241	0.7107	0.7500	0.7707	0.7826
		0,05	0.6153	0.6910	0.7185	0.7306	0.7295
		0,075	0.6078	0.6683	0.6846	0.6796	0.6582
		0,1	0.5982	0.6439	0.6443	0.6171	0.5618
0,4	TRANSACTION COSTS	0	0.5538	0.6699	0.7289	0.7646	0.7873
		0,025	0.5434	0.6513	0.7025	0.7302	0.7443
		0,05	0.5373	0.6338	0.6713	0.6869	0.6873
		0,075	0.5271	0.6098	0.6352	0.6343	0.6168
		0,1	0.5184	0.5858	0.5947	0.5718	0.5208
0,5	TRANSACTION COSTS	0	0.4649	0.6009	0.6700	0.7130	0.7404
		0,025	0.4517	0.5827	0.6415	0.6750	0.6947
		0,05	0.4393	0.5612	0.6095	0.6287	0.6357
		0,075	0.4280	0.5388	0.5722	0.5773	0.5606
		0,1	0.4203	0.5152	0.5318	0.5152	0.4672

No difference appears with results from the case study. In particular: i) the optimal RE level is much higher the greater the waste market dynamicity; ii) the optimal level of redundancy is much lower the higher transaction costs. These general results are useful to confirm my simulation model and make generalizable results of the discussed case study.

6.4 Discussion

Results from agent-based simulation confirm the theoretical framework presented in Section 6.1, i.e., that an optimal redundancy of IS linkages able to maximize the ISN sustainability exists. Such a redundancy is representative for an optimal trade-off between efficiency and resilience of the ISN. However, the optimal redundancy is different depending on both market dynamicity and transaction costs. In fact, the higher the waste market dynamicity, the higher the optimal level of redundancy will be, *ceteris paribus*. When firms adopt high-redundancy strategy collaborating with more other firms, it is simple to reorganize the symbiotic flows in case of disruptive events, thereby avoiding to dispose wastes of in the landfill and to purchase virgin inputs from the related markets. Similarly, the lower the transaction costs arising from the IS exchanges, the higher the optimal level of redundancy will be, *ceteris paribus*. In fact, if transaction costs are negligible compared to the economic benefits stemming from IS, the higher redundancy ensures higher resilience to perturbations without significantly decrease the economic efficiency of transactions. In such a case, the overall effect on the ISN sustainability is positive and increasing the redundancy of symbiotic relationships would be convenient for firms. Alternatively, the higher the weight of transaction costs on the economic benefits created by IS, the lower the redundancy that is convenient to implement. While for top-down ISNs the level of redundancy can be designed *a priori*, redundancy of self-organized ISNs arises from decisions of single firms, which are willing to maximize the economic benefits in their advantage. In this regard, simulation results might be useful for firms, providing them with the redundancy strategy which maximizes the economic benefits. When transaction costs are low, the interactions among firms ensure that the ISN simultaneously maximizes the environmental benefits generated. Alternatively, in presence of high transaction costs, the interactions among firms do not allow to maximize the environmental benefits created by the ISN over the long period. In particular, the environmental sustainability is maximized for a higher level of redundancy rather than the strategy chosen by firms. In fact, despite cooperation with a further partner would increase the amount of material saved, thus generating additional environmental benefits, it would not be economically convenient, since costs arising from such an additional relationship would be higher than the gross economic benefits created. Therefore, in such a case symbiotic opportunities able to create environmental benefits may be not exploited by firms. This is an interesting result because it highlights a potential limit of self-organized ISNs so far unknown. In order to overcome such a limit, the transaction costs of IS relationships should be reduced as much as possible. Transaction costs arise in form of search, negotiation, and enforcement costs. In this regard, online platforms allowing firms to interact and manage their waste exchanges should be promoted with this aim. Moreover, the case of NISP in Great Britain is an example of how firms can receive informational support about the best options to exploit wastes, from the technological and economic point of view, and be helped in seeking suitable partners and negotiate the economic agreement with them (Mirata, 2004). Both these measures allow firms to reduce in particular search and negotiation costs.

Furthermore, results showed that, when transaction costs are low, redundancy has a moderator effect on the negative impact of high market dynamicity. This is an interesting issue. Both the literature and empirical observations highlight that ISNs are less likely to emerge in environmental characterized by high waste market dynamicity, since such a dynamicity makes difficult to create enough waste flows. However, our results showed that enough waste flows can be created also in high-dynamic environments, as long as high redundancy strategy is adopted. This is due to the flexibility in waste exchange offered by having more symbiotic partners, which allows to create more stable IS relationships. Thereby, reducing transaction costs of IS relationships is much more important, since it may support the creation of ISNs even in high-dynamic environments, thus exploiting symbiotic opportunities that are now underdeveloped.

Conclusions

Self-organized ISNs are a tool still underdeveloped in terms of practical applications compared to theoretical opportunities. Such an underdevelopment is due to the low emergence of self-organized ISNs and the low sustainability of these networks over the long period. This thesis has aimed to contribute to the development of the IS practice by addressing both issues, offering both practical solutions and knowledge. In particular, practical solutions allowing firms to overcome two barriers hampering the creation of IS relationships have been provided, with the aim to support firms to implement the IS approach, thus forcing the emergence of self-organized ISNs. Moreover, knowledge about how sustainability of self-organized ISNs depends on a proper balance between efficiency and resilience of the symbiotic network has been developed.

The literature recognized that many firms are reluctant to adopt the IS approach because of low awareness about how to introduce such an approach within their business practice and about possible business scenarios arising from cooperation among different firms. In order to force the development of self-organized ISNs, it is important to make firms aware of business models supporting the IS practice. Firms with such an awareness can choose what business model to implement. Hence, I formalized and investigated the business models that firms can adopt to implement the IS practice ("internal exchange" and "external exchange" for firms producing wastes, "input replacement" and "co-product generation" for firms using wastes) and discussed the business scenarios arising from the cooperation among firms. For each business model, I highlighted how the firm can propose, create, and capture the value by implementing the IS practice. Moreover, for each business scenario, I highlighted strengths and weaknesses related to its implementation.

Online communication platforms are arising with the aim to ensure the match between supply and demand of wastes, then further fostering the creation of new IS relationships. Part of these platforms actually implements algorithms suggesting firms with feasible IS relationships. However, these algorithms currently focus only on the "input replacement" model, identifying and suggesting the inputs that each waste can replace and the wastes that can replace each input. Conversely, platforms should take into account also the "co-product generation" model: updating the search algorithms in such a direction may be useful in order to further promote the IS approach, since firms can discover symbiotic opportunities so far unknown.

Moreover, the economic benefits stemming from IS are often unfairly shared among the involved firms. Firms gaining scant part of the economic advantages have low willingness to cooperate with firms gaining the highest part of these benefits. The literature recognizes that this is an important barrier hampering the development of self-organized ISNs. In this regard, I investigated how the economic benefits created by the IS practice can be fairly shared among firms, increasing their willingness to cooperate. I recognized a problem of incentives misalignment among firms and, by using the lenses of supply chain management, I designed a contract able to modify how the economic benefits stemming from IS are shared among the involved firms, assuring win-win conditions, i.e., that: i) the economic benefit of all firms is increased in the case of IS compared with its absence; ii) the economic benefits are enough to motivate each firm to cooperate. Simply defining a contractual scheme in which one firm pays for the supply of the waste or for the purchase of the waste, the incentives of both parties in the symbiotic relationship are aligned. Moreover, I developed a simulation model to carry out a simulation analysis aimed at investigating the efficacy of the proposed contractual mechanism as a way to foster the formation of ISNs in different scenarios, characterized by increasing levels of uncertainty and turbulence of the external environment as well as trust. In order to do this, I framed ISNs as CASs, following a recent trend of the literature. The simulation analysis confirmed that a contract fosters the emergence of an ISN. Furthermore, the online communication platforms could integrate their current algorithms in order to suggest the optimal contractual clauses able to fairly share the economic benefits among firms.

However, simply forcing the creation of self-organized ISNs is not enough for the development of the IS practice, if these networks are characterized by low sustainability over the long period, i.e., if they are unable to create benefits with continuity over time. Despite the literature recognized the existence of such a problem, the ISN sustainability was a topic still unexplored and a theoretical framework was lacking, since the literature focused so far on providing contributions about the creation of ISNs. Since ISNs are recognized as the analogous of the natural ecosystems in ecology and these ecosystems are characterized by high sustainability over time, I analyzed the problem by taking contribution from such a field. Sustainability of natural ecosystems is related to an optimal balance between two features of the system: efficiency in using resources and resilience to perturbations. Firstly, I analyzed these properties in other fields where they were investigated in depth (the industrial field for the efficiency, ecological, complex, and engineering systems for the resilience) with the aim to identify their antecedents. Then, I developed a theoretical framework for efficiency and resilience of ISNs and I proposed numerical measures to assess both of them. Applications were analyzed in order to show how to compute these measures and to highlight practical implications for both of them.

In particular, I proposed the concept of technical exchange efficiency of ISNs, measuring how efficiently the symbiotic exchanges among processes in ISNs occur. Technical exchange efficiency of ISNs is maximized when there is perfect balance between the amount of produced wastes and the amount of required primary inputs, i.e. when perfect symbiosis occurs within the ISN. Increasing the technical exchange efficiency of a given ISN may allow to increase the technical production efficiency of that ISN, i.e., the efficiency with which the industrial system uses resources and produces wastes. In fact, I showed that the effect of implementing IS among a given set of production processes is the same of technological innovations on each of the involved process, able to reduce the amount of at least one required input or at least one produced waste at equal input generated. Therefore, increasing technical exchange efficiency allows to fully exploit the potentialities of IS in generating advantages for firms involved and for the collectivity. For this reason, it is important that ISNs will be characterized by high technical exchange efficiency. To support the efficiency evaluation, I designed a measure of technical exchange efficiency based on an enterprise input-output model. Such a measure ranges between zero and one: it is equal to zero when no symbiosis occurs in the ISN whereas it is equal to one when perfect symbiosis occurs. Low value of technical exchange efficiency is due to misalignment between the amount of wastes produced and the amount of correspondent inputs required. In this regard, the up-stream and down-stream efficiency measures help to better identify the cause. In particular, the up-stream efficiency is low when waste supply is lower than demand, i.e., when high quantity of inputs has to be purchased from outside the ISN. On the contrary, when waste supply is higher than demand, i.e., high quantity of wastes has to be disposed of in the landfill, the down-stream efficiency is low. Moreover, I integrated such a framework in order to take into account the economic performance of ISNs. In fact, maximizing technical exchange efficiency allows to maximize the gross economic benefits stemming from the IS practice. However, the economic benefits as a whole are maximized when the additional costs of IS relationships are minimized at the same time, i.e., when the redundancy of IS linkages is minimized. Accordingly, I proposed a measure of economic exchange efficiency providing indications about how the ISN is effective in generating economic benefits for firms.

The constantly increasing impact that the disruptive events have on the sustainability of ISNs demonstrates that ISNs should be characterized by an adequate level of resilience. I provided a contribution to this line of research by offering a new conceptualization of resilience in ISNs, reviewing the studies analyzing resilience of ecological, complex, and engineering systems. In doing so, I differ from previous studies on resilience in ISNs, which have mainly conceptualized it in terms of vulnerability and adopted network measures to assess it. My conceptualization of resilience is mainly drawn from ecological systems literature and focuses on the antecedent role of diversity and ubiquity. I provided a conceptualization of both variables in the ISN context, which differ from previous ones given in the literature, and build a resilience index depending on both of them. In particular, network diversity refers to the number of wastes exchanged within the ISN, whereas firm diversity is a function of the number and quantity of diverse wastes a firm produces and uses. Waste ubiquity refers to the number of firms that produce and use that waste. At equal firm diversity, a firm's resilience index is higher, the greater the ubiquity of the wastes that the firm exchanges. At equal waste ubiquity, the higher a firm's diversity, the lower its resilience index. Resilience is also affected by network diversity: the higher it is, the greater the capacity of the ISN to reorganize its waste flows in case of disruption. Thus, firms producing and using a great number and a large quantity of wastes with low ubiquity are critical for ISN survivability. The proposed resilience index ranges between zero and one. In particular, a resilience index equal to zero identifies firms that are highly critical for an ISN's survivability. The removal of these firms causes the collapse of the entire ISN. In contrast, in case of the removal of a firm characterized by high value of resilience index, i.e., producing or using a low number of wastes with high ubiquity, the network can easily reorganize the structure of waste flows.

Finally, the mutual relationships between efficiency and resilience of ISNs have been analyzed. Similarly to natural ecosystems, I found that efficiency and resilience of ISNs are two inversely related properties. In particular, both of them depend on the redundancy of the symbiotic linkages among firms belonging to the ISN: increasing such a redundancy, the ISN efficiency is reduced and the ISN resilience is increased (because of improvements in waste ubiquity). Then, I investigated the effect of different levels of redundancy on numerical measures of economic and environmental sustainability of ISNs by adopting an agent-based simulation approach. In particular, the effect of redundancy was analyzed for different scenarios characterized by different levels of waste market dynamicity and transaction costs. Simulation results showed that the optimal level of redundancy, able to maximize both the ISN sustainability measures, is much higher the greater the waste market dynamicity, *ceteris paribus*, and much lower the greater the transaction costs, *ceteris paribus*. For top-down ISNs, the optimal level of redundancy can be designed *a priori*. Alternatively, redundancy in self-organized ISNs spontaneously arises from choices of single firms about how many partners to cooperate with. In this case, firms can use results from simulations to their advantage, choosing the optimal level of redundancy maximizing the economic sustainability, so maximizing their economic gains from the IS practice.

However, results showed that high transaction costs cause misalignment between economic and environmental sustainability. In particular, given the optimal level of redundancy maximizing the economic sustainability, having an additional partner would increase the environmental benefits created but the costs to manage the additional relationship would be higher than the gross economic benefits stemming from such a relationship. Therefore, since firms would be interested to adopt the level of redundancy maximizing their economic benefits, opportunities to further reduce the environmental impact of the industrial system are lost. Such a problem was unknown so far. However, the misalignment between economic and environmental sustainability does not occur when transaction costs are low. Furthermore, scenarios characterized by low transaction costs and high redundancy are those showing the highest level of both economic and environmental sustainability. High redundancy limits the negative impact of disruptive events on the match between demand and supply of wastes. In fact, if a firm increases the amount of waste it produces, the probability that the additional amount would be used as input by another firm increases with the number of its symbiotic partners. Similarly, if a firm receives lower amount of waste from one of its partners, the probability that it can receive additional amount of waste increases with the number of its symbiotic partners. When the transaction costs are low, the practice to manage more than one partner is economically sustainable over the long period.

These results suggest that the role of transaction costs on the ISNs sustainability is fundamental. In particular, in order to enhance both economic and environmental sustainability of ISNs, it is important to ensure low transaction costs for symbiotic partnerships. Online communication platforms are recognized able to ensure low search costs for symbiotic partners. Moreover, since firms may have access to a wide range of information, these platforms contribute to: i) ensure high match between demand and supply of wastes, which is the main antecedent of the technical exchange efficiency of ISNs; and ii) ensure the possibility that firms can cooperate with more partners, thus increasing the redundancy of the IS linkages, which is one of the main antecedents of the IS resilience. Moreover, if the platform suggested to firms the optimal contractual clauses to fairly share the economic benefits among firms, as previously stated, the transaction costs will be further reduced. These issues show new light on the role of online platforms in forcing the development of the IS approach. In fact, despite these platforms are currently recognized useful in supporting the creation of new IS relationships, this work suggests that communication platforms may have a fundamental role also in increasing sustainability of ISNs over the long period, hence increasing the effectiveness of ISNs in providing benefits.

Despite this thesis was focused on self-organized ISNs, results can be useful also for the design of top-down ISNs. In fact, indications are provided about: i) what symbiotic business scenarios can be designed; ii) how contractual clauses to share the economic benefits among firms can be designed; iii) how to create ISNs sustainable over the long period by designing *a priori* the optimal level of redundancy of symbiotic exchanges.

Moreover, a further contribution of this thesis concerns a methodological advance in the study of the self-organized IS. Firstly, I provided contribution about the adoption the EIO approach to model the network of symbiotic exchanges. The EIO approach allows to overcome the limit of MFA approach in modeling dynamic flows over time. Despite the EIO approach was adopted to model IS exchanges among joint production chains, no previous contributions used it to model the exchanges among single production processes, thus increasing the level of detail. Moreover, the waste treatment processes were not modeled so far. Furthermore, I proposed the use of the agent-based simulation approach to study the spontaneous emergence of self-organized ISNs and their sustainability over the long period.

This study presents some limits. Firstly, despite it recognizes that firms can adopt different business models to support the IS approach, the analysis is limited to the "external exchange to input replacement" scenario, arising when firm producing wastes adopts the "external exchange" business model and firm using wastes adopts the "input replacement" business model. This occurs because such a scenario is the most adopted one, and therefore results from this work are useful immediately. However, further research is needed in order to analyze the other business scenarios. Moreover, other limits have to be acknowledged about: i) the contractual clauses proposed to fairly share the economic benefits among firms; ii) numerical measures of efficiency and resilience; and iii) the agent-based models adopted.

Firstly, the contractual clause I proposed to fairly share the economic benefits among firms is very simple, since it takes only into account the transfer price related to the waste exchange. However, it does not consider other contractual terms as penalties or the time horizon for the symbiotic exchanges. Nevertheless, this simple contract proved to be effective in forcing the arise of self-organized ISN. Then, the study of more complex contractual mechanisms is a subject for future research.

Furthermore, efficiency measures do not take into account the different environmental impact that different wastes and inputs can generate. Currently, the EIO approach provides indications about strategies able to increase the technical and economic exchange efficiency of ISN; however, it is important to recognize what is the best strategy from the environmental point of view, especially when designing the evolution of existing ISNs. Furthermore, the resilience index proposed is static even though developed in concert with a dynamic conceptualization of resilience. Moreover, it does not take into account the economic value of replaced inputs and not-disposed wastes, and, similarly to the efficiency measures, the environmental impact due to their production and disposal. Further research should be devoted to improve both the efficiency and resilience measures. Nevertheless, results of Chapter 6 are independent on these limits.

The agent-based models adopted in this thesis present three main limits. *In primis*, they analyze simple cases of IS relationships, where each firm only produces one waste and requires one input. Even if this is a real situation, and therefore results from these models are significant, firms may be involved in more complex exchanges involving more than one input and one waste (see for instance the case of the Kalundborg ISN discussed in Section 5.5.2). Moreover, the models do not take into account the possibility to stock wastes and inputs. This strategy could be useful in order to artificially reduce the waste market dynamicity, which has proved to have a negative impact on the ISN sustainability. However, by adopting this strategy, new additional costs arise. Hence, further investigation about the role of waste and input stock is required. Finally, the agent-based models developed do not take into account in exhaustive manner the social ties linking the firms. Despite firms are willing to cooperate only if they gain economic benefits from such a cooperation, the important role of social relationships in supporting symbiotic exchanges is recognized. Therefore, future research would be focused on the introduction into the agent-based models of social relationships among firms and the treatment of trust as a dynamic variable resulting from social interactions and evolution of firm.

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