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EXPLORING THE ROLE OF CONTRACTS IN SELF-ORGANIZED INDUSTRIAL SYMBIOSIS: AN AGENT-BASED SIMULATION STUDY

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EXPLORING THE ROLE OF CONTRACTS IN SELF-ORGANIZED INDUSTRIAL SYMBIOSIS: AN AGENT-BASED SIMULATION STUDY

Abstract

This paper explores the efficacy of contractual mechanisms for enhancing the formation of self-organized industrial symbiosis networks in environments characterized by diverse levels of uncertainty and turbulence. We propose a simple contract scheme designed to foster the formation of stable industrial symbiosis relationships and to guarantee that the industrial symbiosis is beneficial for all parties involved. Industrial symbiosis networks are framed as complex adaptive systems and an agent-based model is provided, to study the effect of the proposed contract on their emergence. In particular, we develop a real case study and by means of simulation assess the benefits associated with the proposed contract in terms of emergence of stable industrial symbiosis relationships. The results show that the proposed contractual mechanism is a facilitator for establishing symbiotic relationships especially in scenarios characterized by low environmental uncertainty and high turbulence.

1. Introduction

Industrial symbiosis (IS) concerns the cooperative exchange of resources through business networks aimed at achieving at the same time economic, environmental, and social advantages (Mirata, 2004). Examples of industrial symbiosis networks (ISNs) are spread all over the world, both in underdeveloped economies as well as in developed countries, confirming that IS is an effective strategy to pursue eco-sustainable development (e.g., Lambert and Boons, 2002; Chertow and Lombardi, 2005; Park et al., 2008; Yang and Feng, 2008). Nevertheless, this phenomenon appears to be underdeveloped and not fully exploited.

A clear understanding of the reasons of this underdevelopment is lacking to date. Literature has in fact mainly investigated the mechanisms of inter-firm symbiotic resource exchanges, whilst has devoted less attention to study the creation, the development, and the stability of ISNs. In particular, little in-depth analysis has been performed to determine which factors can obstruct their formation and how to overcome their negative effects.

In this paper we first investigate this issue by recognizing the existence of an incentive misalignment problem for the firms involved in cooperative symbiotic exchange, which limits the formation of stable industrial symbiotic relationships and then address the problem by designing a proper mechanism to handle it. So doing, our study provides contributions to policy makers interested in implementing strategies and mechanisms both to foster the formation of ISNs and to cultivate their stability over time.

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., channel efficiency (Tsay et al., 1999; Cachon, 2003). It is widely recognized that firms are not prone to integrate with each other, unless there is a central authority governing the entire system. To push independent firms to pursue channel integration, proper supply contracts should be adopted (Tsay et al., 1999; Cachon, 2003; Giannoccaro and Pontrandolfo, 2004). In light of this analogy, we suggest 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, we design a contract aimed at: 1) increasing the probability of establishing a stable ISN as a system level goal and 2) satisfying the *win–win* condition. This second condition is required to guarantee a spontaneous emergence of a symbiotic relationship.

In approaching this problem, we frame ISNs as complex adaptive systems (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, 1995, 2002). In doing so, ISNs are studied as an emergent process arising from the spontaneous decisions of independent but interconnected firms. This framework provides the theoretical foundation to develop an agent-based model of the formation of IS relationships. 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 (Epstein and Axtell, 1996; Axerold, 1997; 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 our understanding of certain fundamental processes (Epstein and Axtell, 1996; Axelrod, 1997). Furthermore, it is a valuable tool for building new theories, concepts, and knowledge about some processes (Carley and Gasser, 2000).

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.

The paper is organized as follows. First, we provide a literature review of IS and then we discuss the theoretical background with the aim of identifying the main drivers of, and obstacles to, self-organized IS. We then present the agent-based model of an ISN, where the symbiotic relationships are described by means of an input-output approach. In Section 4, we describe the simulation analysis carried out on an exemplar case driven by empirical data. Finally, a discussion of the results of the simulation analysis is provided.

2. Theoretical background

2.1 Industrial symbiosis networks

IS 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 (Mirata, 2004). Resource flows mainly involve the physical exchange of materials, energy, water, and by-products (Chertow, 2000), but also may include information exchange (Chertow, 2004). The basic mechanism of IS is that one firm's waste can become another firm's feedstock (Frosch and Gallopoulos, 1989). The economic benefit associated with IS mainly consists in improved efficiency thanks to the reduction in raw material purchase costs and waste disposal costs. The environmental and societal advantages come from reducing resource consumption and mitigating environmental pollution (Erkman, 1997; Chertow and Lombardi, 2005).

Given the important economic and social role of IS, the study of the factors leading to the formation and development of stable symbiotic relations among firms in an important topic of analysis. There are two schools of thought regarding this: the former arguing that ISN should be "designed" by adopting a top-down approach, such as the eco-industrial park model (Boons and Baas, 1997; Park et al., 2008, van Berkel et al., 2009; Chao et al., 2010; Shi et al., 2010; Zhang et al., 2010; Behera et al., 2012); the latter affirming that ISNs should be allowed to emerge from the bottom, as the result of a spontaneous, self-organized process undertaken by the firms involved (Heeres et al., 2004; Gibbs and Deutz, 2007; Chertow and Ehrenfeld, 2012).

Empirical cases, such as the Kalundborg in Denmark and the National Industrial Symbiosis Programme (NISP) in the United Kingdom, demonstrate that both these models can be successful (e.g. Mirata, 2004; Jacobsen, 2006). 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). Thus, we focus on this model.

Table 1 summarizes the main features of some self-organized ISNs found in the literature.

Table 1. Empirical cases of industrial symbiosis networks.

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	Jacobsen, 2006; Ehrenfeld and Gertler, 1997
Guayama, Puerto Rico	Coal-fired power plant, chemical refining, pharmaceuticals	Wastewater, condensate, steam, ash	10~20	Hub-and-spoke	Chertow and Lombardi, 2005
Shenzhen Huaqiang Holdings Ltd. (formerly 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, Korea	Oil, chemicals, incineration, metal processing, paper milling	Wastewater, biogas, steam, metal	>500	Hub-and-spoke	Behera et al, 2012
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
UK Industrial Areas	Coal-fired power plant, oil refining, plastic, rubber, plastic recycling, paper milling, chemicals, food and fish processing, metals, furniture	Steam, electricity, technology, waste carpets, fuels, edible oil, electronic waste	>500	Core-periphery	Mirata, 2004

2.2 Self-organized ISNs: A complex adaptive systems approach

Following a recent trend of the literature, self-organized ISNs are framed as Complex adaptive systems (CASs) (Chertow and Ehrenfeld, 2012). 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, 1995, 2002). 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).

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, we identify the following elements: 1) the firms with their specific attributes and goals (agents), 2) the networks among firms (interconnectedness), and 3) the path dependence (Table 2).

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 (Esty and Porter, 1998; Jackson and Clift, 1998; Chertow and Lombardi, 2005; Chertow and Ehrenfeld, 2012).

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 of investment, the size of capital invested and the payback time of the investment (Mirata, 2004). We 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).

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 (Granovetter, 1985; Boons and Howard-Grenville, 2009). There is a trust climate widespread in the industrial network, which is important for sustaining and nurturing the cooperative exchange (Lambert and Boons, 2002; Gibbs, 2003; Gibbs and Deutz, 2007; Hewes and Lyons, 2008). 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 (Jacobsen, 2006; Ashton, 2008). 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 we consider that firms are highly embedded with each other in the social context and that the existence of strong social ties influences the firms' behaviour 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).

Table 2. Framing ISN as CAS.

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

2.3 The importance 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, because 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, we 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) (Christopher, 1992; Bowersox et al., 1999). 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 (Tsay et al., 1999; Cachon, 2003; Tang, 2006; Govindan et al., 2013). 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 our 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 (2008a, 2008b) and Sasikumar and Kannan (2009). The incentive mechanisms used to coordinate the reverse logistics chain are quantity, time, quality, and price/deposit refund (Govindan et al., 2013).

We propose a simple transfer incentive mechanism based on price that is designed to pursue two main goals: 1) to maximize the number of stable IS relationships (system goal), and 2) to assure the *win-win* condition. We discuss the design of the contract later in detail.

2.4 The role of the environment in industrial symbiosis

A dynamic environment affects the emergence of a self-organized complex adaptive system, such as an ISN (Dooley, 1997; Choi et al., 2001). 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 (see Table 1).

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. We 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 1).

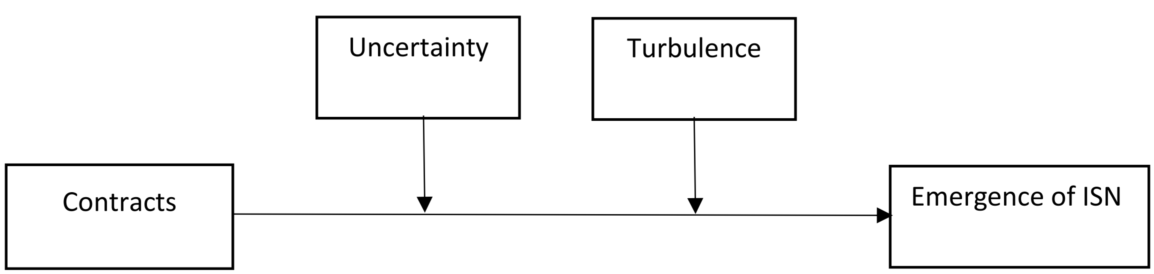

Figure 1. Conceptual framework.

3. The agent-based model of IS driven by the input-output enterprise process

We 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 in 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 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.

Any firm is available to create symbiotic relationships. We 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).

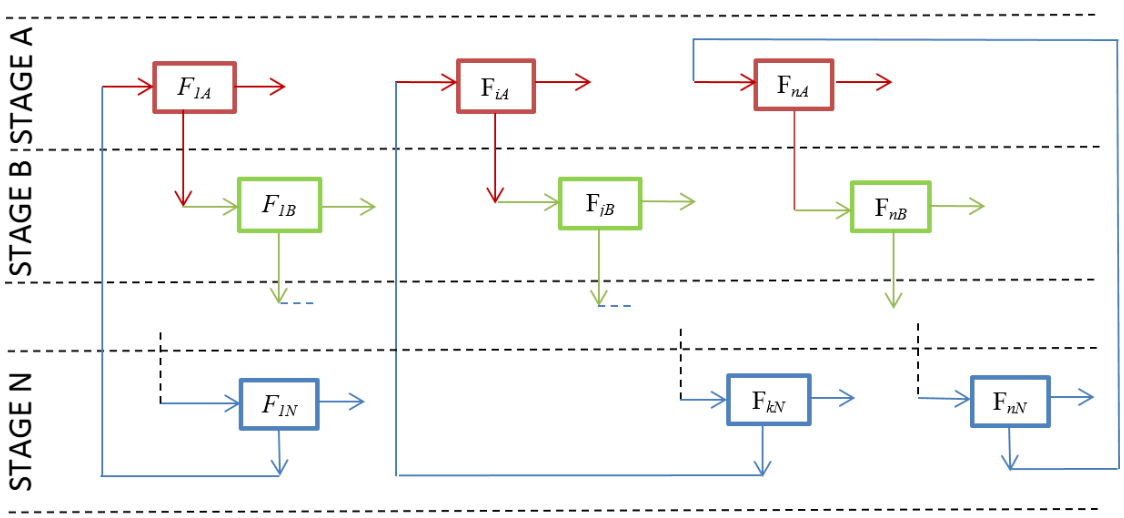

Figure 2. The network of symbiotic relationships.

The symbiotic relationships are modeled by the Enterprise Input-Output approach (Albino et al., 2003; Kuhtz et al., 2010). Notations are given in Table 3.

Table 3. 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*
dc_i	Waste disposal cost paid by firm *i*
pc_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, the waste quantity sent from a generic firm i_A to a generic firm j_B at time t is given as follows:

$$w'_{i_A \to j_B}(t) = \min\{W_A \cdot x_{i_A}(t); R_B \cdot x_{j_B}(t)\} \quad (1)$$

3.1 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, we 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 ($F_{i \to j} > T_i$). 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 (Esty and Porter, 1998; Chertow, 2004; Jacobsen, 2006).

The fitness function is defined as the firm's economic performance. The economic advantage $EB_{i \to j}$ ($EB_{j \to i}$) for firm *i* (*j*) to establish a symbiotic relationship with firm *j* (*i*) is computed as the ratio between the symbiotic advantage $SA_{i \to j}$ ($SA_{j \to i}$), 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. We 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:

$$F_{i\rightarrow j}(t) = \frac{1}{L_{ij}(t)} \cdot EB_{i\rightarrow j}(t) + \left[1 - \frac{1}{L_{ij}(t)}\right] \cdot EB_{i\rightarrow j}(t-1) \tag{2}$$

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 modelled 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 our model thus the level of trust influences the behaviour 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, we define TRUST as the probability of maintaining the relationship, while (1- TRUST) is probability of seeking a new partner.

3.1.1 The economic benefits of industrial symbiotic relationships

We consider that the symbiotic exchange between two generic firms may be ruled by three different contractual options.

The first case consists in the absence of 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:

$$pc_j^{symb} = \beta_{ij} \cdot pc_j \ \text{ with } 0 < \beta_{ij} < 1 \tag{3}$$

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

$$dc_i^{symb} = \alpha_{ij} \cdot dc_i \text{ with } 0 < \alpha_{ij} < 1 \quad (4)$$

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.

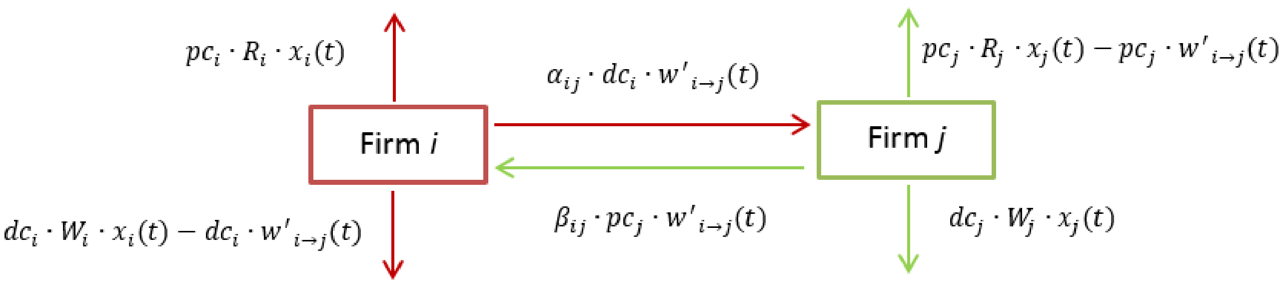

Figure 3. Monetary flows in case of industrial symbiosis.

Table 4 summarizes the three contractual cases examined, showing the value of the symbiotic benefits gained by firms *i* and *j*.

Table 4. The contractual options.

Contractual setting	Contract parameters	Symbiotic benefits
Absence of contract	$\alpha_{AB} = 0, \beta_{AB} = 0$	$SA_{i \to j}(t) = dc_i \cdot w'_{i_A \to j_B}(t)$ $SA_{j \to i}(t) = pc_j \cdot w'_{i_A \to j_B}(t)$
Firm pays to supply its waste	$\alpha_{AB} > 0, \beta_{AB} = 0$	$SA_{i \to j}(t) = (1 - \alpha_{AB}) \cdot dc_i \cdot w'_{i_A \to j_B}(t)$ $SA_{j \to i}(t) = (\alpha_{AB} \cdot dc_i + pc_j) \cdot w'_{i_A \to j_B}(t)$
Firm pays to purchase by-products	$\alpha_{AB} = 0, \beta_{AB} > 0$	$SA_{i \to j}(t) = (dc_i + \beta_{AB} \cdot pc_j) \cdot w'_{i_A \to j_B}(t)$ $SA_{j \to i}(t) = (1 - \beta_{AB}) \cdot pc_j \cdot w'_{i_A \to j_B}(t)$

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:

$$EB_{i \to j}(t) = \frac{SA_{i \to j}(t)}{C_{i_A}(t)} = \frac{\left[(1 - \alpha_{AB}) \cdot dc_i + \beta_{AB} \cdot pc_j\right] \cdot w'_{i_A \to j_B}(t)}{(pc_i \cdot R_A + dc_i \cdot W_A) \cdot x_{i_A}(t)} \quad (5)$$

$$EB_{j \to i}(t) = \frac{SA_{j \to i}(t)}{C_{j_B}(t)} = \frac{\left[\alpha_{AB} \cdot dc_i + (1 - \beta_{AB}) \cdot pc_j\right] \cdot w'_{i_A \to j_B}(t)}{(pc_j \cdot R_B + dc_j \cdot W_B) \cdot x_{i_B}(t)} \quad (6)$$

3.2 The contract design

Our 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, we compute the probability of each of the four events as follows:

$$p_1 = P(F_{i\to j} < T_i) \cdot \left[1 - P\left(F_{j\to i} < T_j\right)\right]$$
$$p_2 = \left[1 - P(F_{i\to j} < T_i)\right] \cdot P\left(F_{j\to i} < T_j\right)$$
$$p_3 = P(F_{i\to j} < T_i) \cdot P\left(F_{j\to i} < T_j\right)$$
$$p_4 = \left[1 - P(F_{i\to j} < T_i)\right] \cdot \left[1 - P\left(F_{j\to i} < T_j\right)\right] \cdot (1 - \mathrm{TRUST})^2$$

Thus, we 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:

$$\overline{EB}_{i\to j} = (1 - p_f) \cdot \frac{\left[(1 - \alpha_{ij}) \cdot dc_i + \beta_{ij} \cdot pc_j\right] \cdot \min\left\{W_i \cdot \bar{x}_i; R_j \cdot \bar{x}_j\right\}}{(pc_i \cdot R_i + dc_i \cdot W_i) \cdot \bar{x}_i} \tag{7}$$

$$EB_{j\to i} = (1 - p_f) \cdot \frac{\left[\alpha_{ij} \cdot dc_i + (1 - \beta_{ij}) \cdot pc_j\right] \cdot \min\left\{W_i \cdot \bar{x}_i; R_j \cdot \bar{x}_j\right\}}{(pc_j \cdot R_j + dc_j \cdot W_j) \cdot \bar{x}_j} \tag{8}$$

3.3 The agent-based model dynamics

The agents of our 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 (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's 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 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.

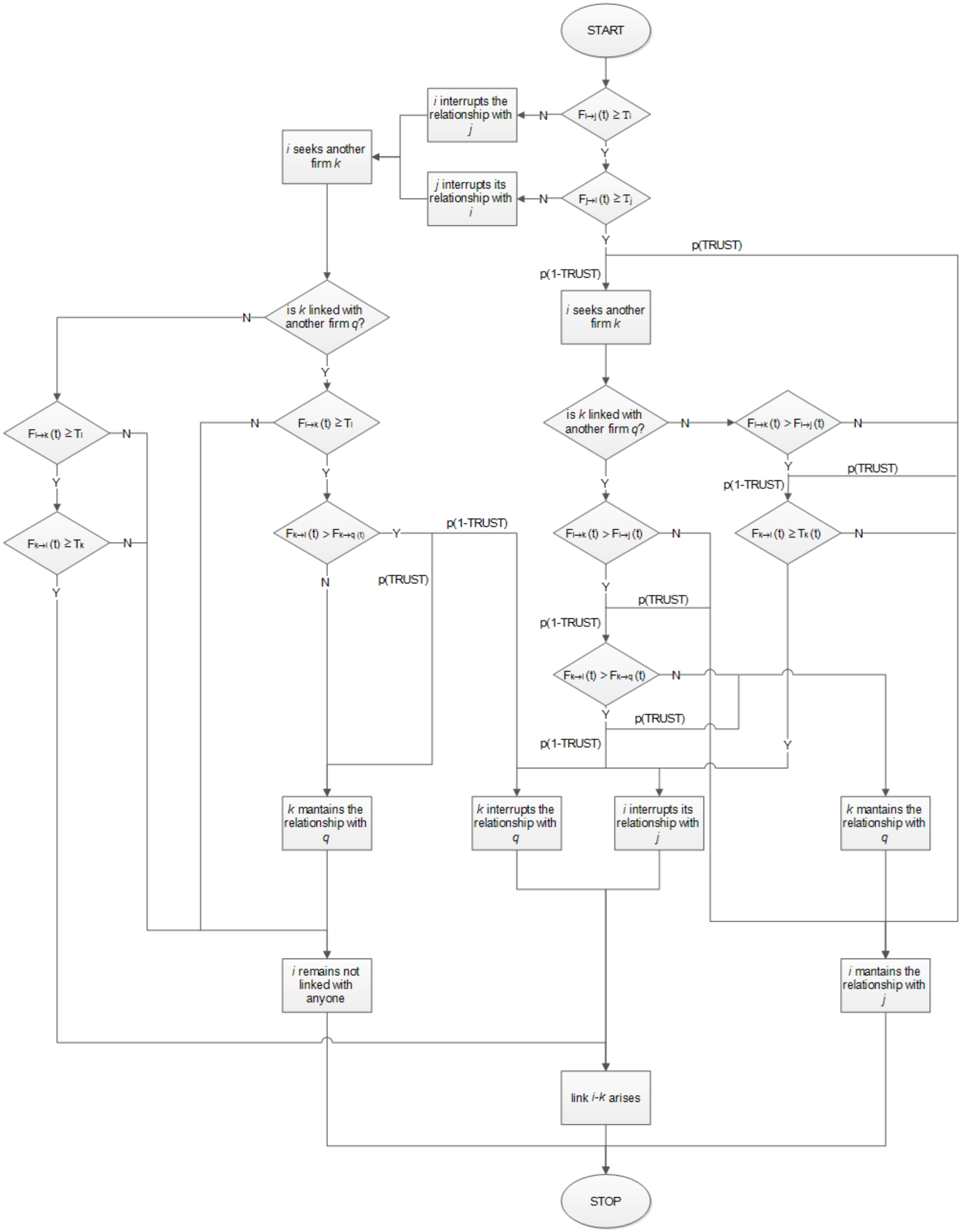

Figure 4. Flow chart of the agent decision making process.

4. Simulation analysis

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 empirical cases. In particular, we 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, we analyzed the effectiveness of the contractual mechanisms to foster the emergence of IS in diverse environments, as proposed in our research question.

4.1 Data

To build our simulation model we 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 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 we 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.

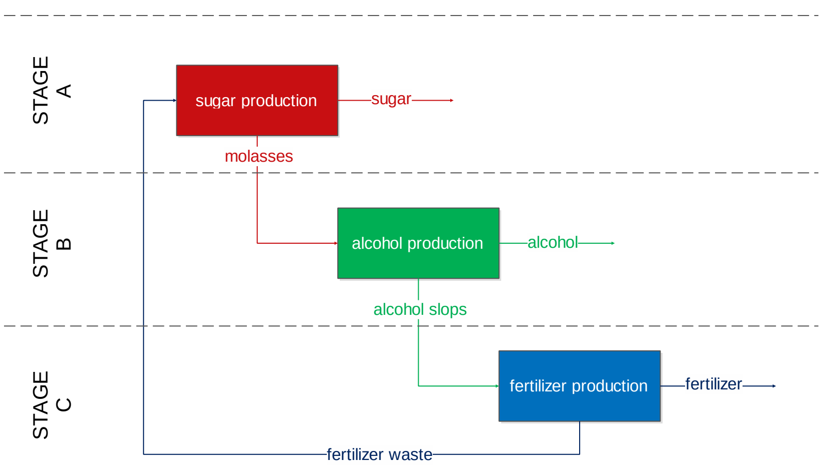

Figure 5. The model of the feasible industrial symbiotic relationships.

Numerical data on the production quantities, the raw material requirements, and the waste produced are shown in Table 5. The values of the technical coefficients for the three stages are obtained from secondary data and shown in Table 6. 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 5. Numerical data (ton per year).

Main product		**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 6. Values of the technical coefficients.

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

4.2 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, we 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 7 summaries the values of all parameters used to define the simulation scenarios.

Table 7. 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

In each scenario, we 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.

5. Simulation results

We 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.

5.1 The baseline model

In Table 8 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 our simulation model, which indeed is able to reproduce the empirical observations and the dynamics identified in the literature.

Table 8. 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)

5.2 The contract case

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

We first designed the contract using the minimization problem presented in Section 3.2. 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 9 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 forth 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 $(\alpha_{ij} \cdot dc_i - \beta_{ij} \cdot pc_j) \cdot \overline{w'}_{ij}$. 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 9. Results in the contractual setting.

(a) 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%

(b) 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%

(c) 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%

(d) 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%

We ran the simulation in the same scenarios as those of the baseline setting. The simulation results are shown in Table 10. 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 10. 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)

We compared the results achieved in the contract and baseline settings (Table 11). 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 range 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 12).

Table 11. Comparison between the baseline and the contract settings (percentage of industrial symbiosis 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 12. 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%**	

6. Discussion and Conclusions

While cooperative resource exchange has been widely analyzed in the literature, few studies have investigated strategies and mechanisms to foster the emergence of stable ISNs. This study fills this gap, by exploring the adoption of contractual mechanisms ruling the symbiotic relationships between firms as an effective way to reach this goal.

Contracts are used to incentivize the parties to follow specific collaborative behaviors, since industrial symbiosis, although beneficial for the system as a whole, could be locally inefficient for the single firm. This requires the establishment of either a central authority imposing IS (the so-called top-down approach) or of a contractual mechanism that incentivize firms to spontaneously pursue it, in a self-organized model. In this work we have borrowed this idea from supply chain management literature, where supply chains, like IS networks, exhibit a misalignment incentive problem to integration and we 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.

In particular, the contract was designed to improve the number of IS stable relationships as well as to assure win-win conditions, i.e., the economic benefit of all firms is increased in the case of industrial symbiosis compared with its absence. Simply defining a contractual scheme in which one firms pays for the supply of the waste or for the purchase of the waste, we aligned the incentive of both parties in the symbiotic relationship. Then, we showed with a case study that the proposed contract, by reducing the probability of failure and guaranteeing the win-win condition, determines both higher economic benefits for all the firms and the emergence of a higher number of stable industrial symbiotic relationships.

Furthermore, we used the 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 stable ISNs in different scenarios, characterized by increasing levels of uncertainty and turbulence of the environment as well as trust.

The simulation analysis confirmed that a contract fosters the emergence of an ISN. This mechanism modifies how the symbiotic economic benefits are shared among the firms involved, thereby influencing their motivation to establish a symbiotic relationship.

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 our analysis, we 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, we find that the proposed contract, based on a transfer payment re-aligning firm incentives to industrial symbiosis, is easy to design and particularly beneficial when environmental uncertainty is not high, while turbulence is high. Thus, the adoption of the proposed contract can 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 paper, merits some comments. Our 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 (Lambert and Boons, 2002; Hewes and Lyons, 2008).

This paper made a methodological advance in the study of the self-organized IS by applying agent-based simulation and providing a quantitative approach, based on enterprise input-output, in order to study industrial network formation, which is generalizable to any network case. To the best of our knowledge, no study using these approaches have been developed to date to study IS.

Finally, our 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 will be focused a) on the study of more complex contractual mechanisms in order to favor the emergence of symbiotic relationships, even in presence of highly uncertain environments, b) on the improvement of the model of the network of the symbiotic relationships, to include all real cases, c) 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.

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