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Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study

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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 utilize 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., 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 (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 or strong social pressures. 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

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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; Axelrod, 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 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 discuss the theoretical background of this study. In particular, we 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 the Methods Section, we 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 4, we discuss the results of the simulation analysis and we test the robustness of the proposed contract. Finally, conclusions are 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.

2.2. Self-organized industrial symbiosis networks: 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

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