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The design of industrial symbiosis: an input–output approach

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ABSTRACT

Industrial symbiosis (IS) has gained more attention in the production economics as the pressure on companies increases for the reduction of waste emissions and primary resources consumption. In fact, this has forced companies to provide other companies their wastes as primary resources and vice-versa. These supply circles lead to IS that can mitigate environmental impacts and costs in industrial areas (IA).

The aim of this paper is to provide guidelines for the future evolution of IA operating on the basis of IS principles. Given a production network within an IA, perfect IS within the network is defined as a theoretical optimum for IS design where no primary resources is needed from outside and no wastes are discharged outside. Adopting an enterprise input–output approach, the conditions for a perfect IS are found for one-waste and multi-waste cases, and the distance between the states of the actual network and of the related perfect IS is measured.

Proposed approach is empirically applied to Santa Croce sull'Arno industrial district of tannery where the recycling of chrome liquors, fleshing, and wastewater are investigated. Results show under which conditions perfect symbiosis is achievable for two waste types. Policy implications are also suggested for the design of IA when IS principles are adopted.

1. Introduction

At the present, there is a need to give further impetus to efficient and eco-innovative production processes, to reduce dependency on raw materials, and to encourage optimal resource use and recycling (UNEP, 2009). Industrial symbiosis (IS) has been considered as one of the effective solutions to reduce the impact of waste emissions and of primary input consumption moving towards sustainable production models.

Industrial symbiosis is a sub-field of industrial ecology, a discipline emerged more than twenty years ago that studies "the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" (White, 1994). In particular, IS operates at the inter-firm level (Chertow, 2000).

Chertow (2007) has defined IS as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2007, p.12). These keys for the success of IS differ according to the case- and location-specificity of IS and they are largely discussed within the recent literature.

In fact, IS can be approached from various perspectives (e.g. social, economic, environmental, spatial, organizational, and technical) where case studies (such as eco-industrial parks) are mostly dominating. Boons et al. (2011) suggest a two level-analysis of IS: (1) regional industrial system (geographic level) and (2) concepts and routines (social level).

From the geographic point of view, Lyons (2007) examines the relationship between geographic scale and loop closing for heterogeneous wastes. His findings show that there is no preferable spatial scale at which loop closing should be organized and loop

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closing is dominated by the transactions deriving from spatial economic logic of the involved firms.

From the social point of view, Mirata and Emtairah (2005) emphasize the importance of stimulating the collective definition of problems and of constructing inter-sectorial interfaces, and defend the significance of inter-organizational culture as a social component of IS. In fact, in some cases collective actions with centralized management are efficient (Jacobsen, 2006), whereas in other cases low cooperation at the level of companies occurs due to the high level of cultural diversity (Korhonen and Snäkin, 2005). Lambert and Boons (2002) describe the IS as a social process where social learning is essential for actors' interaction. In fact, the change towards an effective IS is not simple because of the divergent interests of involved actors, missing collective action and cooperation. Moreover, the success of IS is based on the individual perceptions of decision-makers, driven by their responsibilities and commitment on sustainable development (Posch, 2010). This success is also based on the enabling context (Boons and Baas, 2006) which can be described in terms of cognitive, cultural, political, spatial, and temporal embeddedness of actors. The support of governments (and other institutions) can be crucial to enhance self-organization which remains essential for IS to work (see also Mirata, 2004). Similarly, Costa and Ferrão (2010) suggest that IS has to be supported by the interaction among the government, industries and other institutions in order to share their own strategies.

If the geographic and social points of view are important for understanding IS, the technical level is considered as fundamental for the design of production systems inspired by IS principles.

In this paper, we analyze IS considering materials and energy flows and the related supply-demand match for each waste becoming primary input. This analysis can be useful to set strategies for companies and policies for local governments on how to move towards perfect IS condition.

The perfect IS is defined as the substitution of primary inputs of production processes by wastes of other production processes where there will be no waste to dispose of and no primary input to purchase from external suppliers once the IS is structured within the IS network.

In the next section a specific review of the literature is devoted to the development of models able to investigate IS. The basic enterprise input–output approach and the model of IS for a production system in the one waste and multi-waste cases are described in the third and fourth section, respectively. In section five, the proposed approach is applied to the case study of Santa Croce sull'Arno industrial district of tannery where the recycling of chrome liquors, fleshing, and wastewater are investigated. The paper concludes with discussion and conclusions in the sixth and seventh sections.

2. Literature review and problem statement

From a technical point of view, a production chain can be considered as an input–output system (Storper and Harrison, 1992) that describes the product flows existing among production processes. Input-output systems may involve many production processes, depending on a specific division and classification of production in processes. In general, the chain may contain the extraction of raw materials, manufacturing, distribution and use of goods. Referring to the environmental sustainability, a sustainable production chain means favouring, for a given output, processes with less use of natural resources (energy and materials) and production of wastes. Regarding the chain as a whole, different terms have been proposed by the literature to define the environmental behaviour of the production chain. The concept of the environmental chain (Bloemhof-Ruwaard et al., 1995) has been introduced to focus on the evaluation of the emissions caused by the supply chain in the environment. Differently, the concept of "extended" or "green" supply chain arises as the basic structure of the entire supply chain needs re-definition by accommodating environmental concerns of waste and resource use minimisation (Beamon, 1999). This means that the traditional structure of supply chain must be extended to include mechanisms for materials and energy recovery. In particular, extended supply chains include the reduction and elimination of by-products through cleaner process technologies and lean production techniques. Moreover, this concept raises from the extension of supply chain boundaries as far as to include the source and the destination of all the physical flows used and produced at each supply chain stage. Spatial aspects can also be relevant to evaluate the environmental impact of production chains since environmental and economic performance measures are strongly related with transportation and logistics solutions (Albino et al., 2002, 2008). Then, increasing attention is now paid to operations management in sustainable supply chains (Linton et al., 2007). As the opportunity offered by the efficient use of materials (recycling, etc.) and energy stresses the relevance of network of actors, cooperation between actors becomes crucial. Thus, IS may serve as a sustainable production policy not only at local but also at national levels. For example Dong et al. (2014) analyze the potential carbon reductions thanks to IS implementation in two Chinese cities Jinan and Liuzhou. Their findings showed that 3.9M t CO_2/year in Jinan and 2.3M t CO_2/year in Liuzhou can be reduced.

Cooperation can be considered also in terms of industrial ecology. Frosch and Gallopoulos (1989) introduce the concept of "industrial ecosystem" as a new way to integrate industrial processes that transform raw materials into final products and waste to be disposed of. In fact, the consumption of energy and materials needs to be optimized, waste production reduced, and the outputs of one process have to serve as inputs for other processes. In particular, Gertler (1995) defines an industrial ecosystem as a community or network of companies in a region who interact by exchanging and making use of by-products and/or energy in a way that provides some benefits, such as increased energy efficiency reducing systemic energy use, and reduced waste products requiring disposal. Then, co-location permits the materials/energy exchanging networks to work better (Lowe, 1997).

Based on a taxonomy of eco-industrial parks, Chertow (2000) distinguishes five material exchange types identified as IS: (1) through waste exchanges, (2) within a firm, facility or organization, (3) among firms collocated in a defined eco-industrial park, (4) among local firms that are not collocated, (5) among firms organized 'virtually' in a broader region. Chertow also discusses approaches for sustaining eco-industrial parks. Three possible options are suggested: (1) building on existing types of material or energy exchange, (2) building on preexisting organisational relationships and networks, and (3) the anchor tenant model (i.e. locating one or two large industries which can provide critical mass to eco-industrial parks).

Chertow (2007) also distinguishes between a planned model and a self-organising model of IS. The former refers to conscious efforts to identify firms from different industries and co-locate them so they can share resources across and among them. The latter refers to industrial ecosystems that emerge from the decisions by private actors motivated to exchange resources for economic reasons. Although both models might be used in different specific cases from an organizational perspective, operating IS efficiently and flexibly is a critical success factor for IS networks, which seems to be neglected in case study-dominant IS literature. Knowledge-sharing in the design phase is key to operational success in IS-based business as potential cooperation candidates have usually limited knowledge about each other's production