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Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis

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ABSTRACT

An important challenge that firms should be able to tackle regards the mitigation of the environmental impact of their production processes avoiding additional costs. Using industrial symbiosis (IS), two different firms can obtain mutual environmental and economic benefits, at the same time, exchanging wastes for primary inputs. Industrial symbiosis networks (ISNs), i.e. networks of production processes exchanging wastes among them, are thus emerging and efficiency measures are needed to be defined and investigated, in order to drive the ISN design and development.

In this paper, we develop the concept of technical exchange efficiency of ISNs and develop a measure of such an efficiency. This measure is computed by using an input-output approach at the enterprise level, modelling symbiotic flows within ISNs. A case example is discussed in order to show the practical applications of technical exchange efficiency of ISNs. In particular, technical exchange efficiency of ISNs can be useful in order to drive the development of existing ISNs and to design new industrial systems exploiting the IS approach.

1. Introduction

Industrial ecology is a concept that concerns the interactions between industrial activities and the environment (Graedel, 1994). In particular, industrial ecology analyses materials and energy flows in industry, the effect of these flows on the environment, and the way these flows are affected by economic, political, social, and legal factors (White, 1994).

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in a collective approach to competitive advantage, involving physical exchange of materials, energy and services (Chertow, 2000). This approach allows to achieve economic, environmental, and social advantages for the firms involved and for the entire community (Mirata, 2004). The usefulness of the IS approach to boost resource use and production efficiency has been recognized by European Commission (2011), which has explicitly recommended its implementation. As a result, policymakers of many countries have introduced the IS practice in their environmental agenda (e.g., Mirata, 2004; Mirata and Emtairah, 2005; Van Berkel et al., 2009; Costa et al., 2010). Applications of IS are available in both developing and developed countries, confirming the effectiveness of IS in pursuing eco-sustainable development (e.g., Sakr et al., 2011; Olayide, 2015). Various forms of IS have been recognized (Chertow, 2000, 2007) in terms of spatial scale (within a firm, among firms co-located, among firms not co-located), types of relationship (exchange of wastes and by-products, sharing of services and information), and planning approach (top down, bottom up). These IS forms are the result of the interaction among actors along three different dimensions: technical, economic, and social one.

An industrial symbiosis network (ISN) is a network of production processes among which waste exchanges exist (Fichtner et al., 2005). ISNs can either be designed adopting a top-down approach or, conversely, let emerge from the bottom (Chertow, 2007). The cases of Kalundborg in Denmark and the National Industrial Symbiosis Programme (NISP) in United Kingdom demonstrate that both these approaches can be successful (Mirata, 2004; Jacobsen, 2006).

With the aim to better understand the potentialities of IS approach, several contributions analysing benefits generated by ISNs have been proposed by the literature (Chertow and Lombardi, 2005; Mattila et al., 2010; Sokka et al., 2011). In particular, the reduction in environmental impact of production processes and in production costs generated for the involved firms has been quantified for different case studies. However, such an approach of analysis is unable to provide indications about the extent to which the IS is applied in an efficient manner within a given ISN, i.e. if the benefits currently generated could be further increased by better implementing the IS approach. Accordingly, a measure of efficiency for ISNs is lacking.

In this paper, we contribute to fill this gap by defining the concept

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of technical exchange efficiency of ISNs. A measure of such an efficiency is proposed adopting an input-output approach at the enterprise level (Lin and Polenske, 1998; Albino et al., 2002, 2003) to model production processes generating and requiring wastes, as well as the symbiotic exchanges taking place among these processes. A case example is used to show the computation of technical exchange efficiency and to highlight practical applications of such a measure. In particular, technical exchange efficiency of ISNs can be useful to drive the evolution of existing ISNs, as well as to design new industrial systems exploiting the IS approach.

The paper is organized as follow. Section 2 addresses the topic of IS. Section 3 develops the concept of technical exchange efficiency. In Section 4, the measure of technical exchange efficiency for a generic ISN is developed and presented. Section 5 addresses and discusses the case example. Finally, conclusions are provided in Section 6.

2. Industrial symbiosis

The IS among production processes evokes the metaphor of natural symbiosis among organisms in ecosystems (Ayres, 1989; Korhonen, 2001). In this field, the word "symbiosis", from ancient Greek σύν "together" and βίωσις "living", 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 (Douglas, 1994): mutualism, commensalism, and parasitism. 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 (Ollerton, 2006). Such an exchange allows that both the organisms benefit from 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 (for instance support or locomotion) 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. performance of the other organism is reduced (Table 1).

In the IS context, production processes exchanging wastes for primary inputs correspond to natural organisms exchanging resources for services. Two production processes, A and B, implement a symbiotic relationship when at least one waste produced by the former is used to replace at least one primary input required by the latter (Lombardi and Laybourn, 2012). In such a case, the process B receives one resource (waste) from process A in return for a service provided (B is disposing wastes for A). Accordingly, IS can be conceptualized as a form of mutualistic symbiosis, since the relationship provides both the processes with environmental and economic benefits. In particular, from the environmental point of view, the amount of wastes disposed of in the landfill is reduced for process A, whereas the amount of primary inputs purchased from conventional sources is reduced for process B. Moreover, from the economical point of view, process A benefits from reduction in waste disposal costs whereas process B benefits from reduction in primary input purchase costs (Esty and Porter, 1998; Albino and Fraccascia, 2015; Albino et al., 2016).

Table 1
Impact on two organisms in each symbiosis subcategory.

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

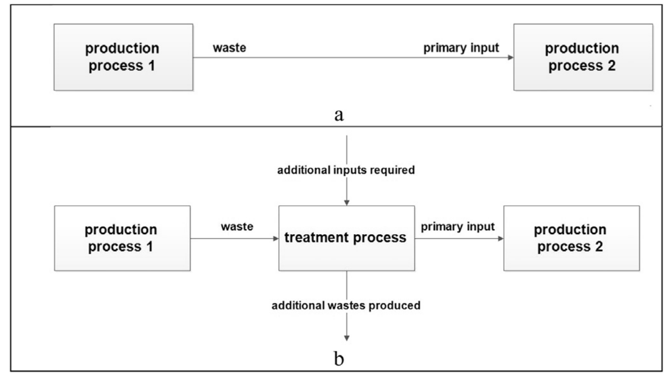

Fig. 1. IS relationship with pure substitution between wastes and primary input (a) and IS relationship with impure substitution between wastes and primary input (b).

Literature has addressed the IS approach from technical, economical, and social point of view.

Two different cases of IS relationships can be recognized from the technical point of view: i) pure substitution between waste and primary input; ii) impure substitution between waste and primary input. Pure substitution occurs if a waste can be directly used in place of a primary input without any treatment process (Fig. 1a). In the case of impure substitution, wastes need to be treated before being used as inputs, i.e. some physical-chemical characteristics of the wastes have to be changed (Eilering and Vermeulen, 2004; Fichtner et al., 2005; Tudor et al., 2007). Hence, treatment processes making wastes suitable to be used as primary inputs have to be introduced. In carrying out this treatment, such processes may require additional primary inputs and energy and may generate additional wastes, in turn generating environmental impact (Fig. 1b). However, the waste exchange is considered an IS process only if such an additional environmental impact is lower than the avoided one due to symbiotic exchange. Hence, although the need to treat wastes, the overall environmental benefits of IS relationships are positive (Mattila et al., 2010, 2012; Sokka et al., 2011).

Literature recognized that the willingness to obtain economic benefit stemming from reduction in production costs or increase in revenues is the main driver that forces firms to implement IS (Esty and Porter, 1998; Lyons, 2007; Paquin et al., 2015). To establish an IS relationship, all the involved firms must achieve higher economic performance than in the absence of the relationship. Hence, IS relationships can arise at several spatial levels and the choice of such a level is dominated by the transactions deriving from the economic logic of the firms involved (Lyons, 2007). Hence, IS relationships may also arise among production processes very far from each other, until these relationships are evaluated as economically convenient by all the involved firms (Sterr and Ott, 2004).

IS relationships may involve production processes belonging to the same firm or conversely belonging to different firms (Chertow, 2000). In the latter case, the effectiveness of IS can be negatively influenced by the diverging interests of involved actors, or by a missing collective action and cooperation (Eilering and Vermeulen, 2004). For this reason, IS has also been largely studied from the social point of view. Most of the literature agrees that trust and collaboration among the involved firms are the key factors for the preservation of IS relationships through time (e.g., Lambert and Boons, 2002; Hewes and Lyons, 2008). In fact, the success of IS is based on the individual perceptions of decision-makers, driven by their responsibilities and commitment on sustainable development (Posch, 2010). Mirata and Emtairah (2005) emphasized the importance of stimulating the collective definition of problems and of constructing inter-sectorial interfaces, and they defended the relevance of inter-organizational culture as a social component of IS. The development of measures able to point out the benefits and the opportunities of IS can strongly support the mutual