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RETHINKING RESILIENCE IN INDUSTRIAL SYMBIOSIS: CONCEPTUALIZATION AND MEASUREMENTS

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Abstract

Resilience has become the new imperative of Industrial Symbiosis research, since its recognition as a fundamental factor in the development of sustainable Industrial Symbiosis Networks (ISNs). We offer a contribution to this topic by providing a wider conceptualization of resilience and an innovative method of measuring it, borrowing from studies in other disciplines such as ecology, complexity science, and engineering. We identify two important antecedents of ISN resilience, i.e., diversity at system and firm level and the ubiquity of wastes, on the basis of which we design a new method of measuring ISN resilience. This captures the extent to which the removal of a firm is critical for the ISN's survival. We test our resilience index on two real ISNs and compare it against other network-based measurement methods commonly adopted in the literature. Finally, we discuss the advantages of the new measurement procedure.

Keywords – Industrial Symbiosis Network, Resilience, Ecological Systems, Diversity, Ubiquity, Measurements

1 Introduction

Industrial symbiosis (IS) is a sub-field of industrial ecology engaging "*traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products*" (Chertow, 2000, p. 313). In particular, wastes and by-products generated by a firm are used as inputs for other firms, generating benefits both for the firms involved in waste exchange and for the collectivity as a whole (Mirata, 2004). Firm benefits are in the form of economic advantages: by exchanging wastes, firms can reduce their production input purchase costs and waste disposal costs (Albino and Fraccascia, 2015). Benefits for the collectivity refer to the environmental and societal advantages, including smaller amounts of primary input used in production processes, less waste disposed of in landfills, and the creation of new jobs (Mirata and Emtairah, 2005). Policymakers in many countries have recognized the importance of IS practice and introduced it into their economic agenda as a tool for reaching a sustainable economic development. For instance, the European Commission has explicitly recommended the adoption of the IS approach to boost resource use and production efficiency (European Commission, 2011).

An industrial symbiosis network (ISN) is a network of firms among which IS relationships exist (Fichtner et al., 2005). According to the 3-2 heuristic logic developed by Chertow (2007), an ISN is defined as a network in which there are at least three different firms exchanging at least two different types of waste. A critical problem of ISNs is that they are extremely vulnerable to perturbations (Ruth and Davidsdottir, 2009; Chopra and Khanna 2014). A perturbation is defined as any event able to affect the feasibility conditions of IS relationships, which ultimately negatively affects the amount of economic benefits that firms obtain from IS. Since the economic benefit is the main driver pushing firms to form and maintain symbiotic relationships, any perturbation may become particularly critical. Any reduction of the economic benefit arising from the IS may be enough to motivate firms to interrupt the symbiotic flows or, in the worst case, to leave the ISN (Mirata, 2004). This might cause the disruption of the ISN as a result of a domino effect due to the interconnectedness among the firms in the ISN. In fact, a firm that leaves the ISN reduces the economic benefits of the firms with which it exchanged wastes (Albino et al., 2016). These in turn can decide to leave the ISN, which may generate a cascade effect that impacts on the rest of the network (Allenby and Fink, 2005; Boons and Spekkink, 2012). Hence, due to close interconnectedness among firms, small perturbations affecting just one or a few firms can have a strongly disruptive impact on the ISN.

To avoid this critical problem, ISNs should be designed to be resilient. Resilience is the property of a system characterized by low vulnerability to perturbations (Holling, 1973). The lower the impact of disruptions on a system’s performance, the higher its resilience will be. A strong relationship exists between resilience and sustainability (Walker at al 2004; Ulanowicz et al., 2009; Derissen et al., 2011). Given this importance, understanding resilience of ISNs has become the new imperative of IS research, whose main attention to date, instead, has been concentrated on studying the emergence of ISNs and mechanisms by means of which to make resource exchanges eco-efficient (Yu et al., 2014). Despite its recognized importance, studies on the resilience of ISNs are still lacking. A recent review by Meerow and Newell (2015) confirms that resilience has not been a research focus of industrial ecology and more in depth of IS. This contrasts with a large and rich body of literature on resilience in other disciplines.

Our aim is to contribute to this topic by proposing a new conceptualization of resilience of ISNs and an innovative way to measure it, borrowing from the studies on resilience in other disciplines such as ecology, complexity science, and engineering. The few previous studies on resilience of ISNs have analyzed it in terms of vulnerability of the system and measured it by using network theory metrics (Zeng et al., 2013; Zhu and Ruth 2013; Chopra and Khanna, 2014). We extend these studies by identifying two main antecedents of ISN resilience. These antecedents are diversity at network and firm levels and ubiquity of the waste exchanged. The proposed conceptualization is aimed at designing a specific method for the measurement of ISN resilience, based on the assessment of firm and network diversity and waste ubiquity, thus capturing the effective sources of resilience in ISNs.

The paper is organized as follows. In Section 2, a literature review on the resilience of ecological, complex, and engineering systems is presented. In Section 3, a conceptualization of the ISNs resilience is proposed, based on the antecedents previously identified. In Section 4, the new ISN resilience measurement index is proposed. In Section 5, we test the resilience index on two real ISNs. Finally, discussion and conclusions are presented in Section 6.

2 System resilience: a literature review

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

2.1 Ecological literature

Resilience was introduced to the ecological literature by Holling (1973), who stated that "*resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and* *parameters, and still persist*" (p. 17). The feature of resilience emerges during the transition of an ecosystem between two equilibrium states. When the first equilibrium state is lost due to a perturbation, the system has to react in order to regain an equilibrium state (Holling, 1973). In this regard, two schools of thought can be distinguished (Holling, 1996). The first sustains that the ecosystem returns to its initial equilibrium state after the perturbation. Accordingly, resilience of an ecosystem is defined as "*how fast the variables return towards their equilibrium following a perturbation*" (Pimm, 1984, p. 322). Hence, this definition refers to a static conceptualization of resilience. The second school recognizes that ecosystems are complex systems able to evolve over time. Hence, rather than return to its state before the perturbation, such a system may evolve towards a new equilibrium state different from the previous one (Gunderson, 2000). In accordance with this point of view, Walker et al. (2004) defined resilience as "*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*". This definition refers to a dynamic conceptualization of resilience. It is considered as an emergent property related to the self-organized behaviour of the ecosystems over time (Gunderson, 2000). This concept of resilience of ecological systems is further developed by Walker et al. (2004), who distinguish four dimensions of resilience: *latitude, resistance, precariousness,* and *panarchy*. *Latitude* is defined as the maximum amount a system can be changed before losing its ability to reorganize within the same state. *Resistance* refers to the facility or difficulty of changing the system, i.e. how resistant it is to change. *Precariousness* is related to how close the current trajectory of the system is to a threshold that, if breached, makes reorganization difficult or impossible. Finally, *panarchy* is related to how the above three components are influenced by the states and the dynamics of the subsystems at scales above and below the scale of interest. Systems characterized by different combinations of these components can have equal ability to maintain their functions under disruptive events.

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

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

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

2.2 Complex systems literature

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

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

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

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

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

This approach considers resilience in terms of end outcome: accordingly, the system is much more resilient to disturbance, when the likelihood is high of a positive or neutral outcome following a disruptive event. In line with this approach, with specific focus on natural disasters that stress human communities, the English Department for Internal Development (DFID, 2011) provides a measurement scale of resilience, consisting of four possible system outcomes as reaction to a disturbance: i) bounce back better; ii) bounce back; iii) recover but worse than before; and iv) collapse. A system able to achieve a "bounce back" outcome after a disruptive event is more resilient (with respect to the specific disruption) than another system whose outcome after the same disruption is "recover[y] but worse than before" or "collapse". In this sense, resilience depends on the adaptive capacity of such systems, since this feature is related to the capacity to provide answers to changes (Smit and Pilifosova, 2001; Smit and Wandel, 2006).

Differently from the previous one, the *process-based* conceptualization focuses on the ability of systems to absorb events, using predetermined coping responses (Cutter et al., 2008). This characteristic is known as the absorptive capacity of the system. In a system with an adequate absorptive capacity, the impact of disruptive events can be attenuated, compared with other systems with a lower absorptive capacity. Hence, the greater the absorptive capacity of the system, the higher its resilience will be.

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

2.3 Engineering Systems literature

Resilience of engineering systems is defined as the "*ability of a system to sense, recognize, adapt and absorb variations, changes, disturbances, disruptions and surprises*" (Hollnagel et al., 2007, pp.3-4) or similarly as "*the joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation*" (Ouyang, 2014, p.53). Therefore, resilience of engineering systems has been investigated with reference to a static conceptualization, coherently with the first school of thought of the ecological studies on resilience.

Studies on the resilience of the engineering systems have analyzed transportation infrastructures (Nagurney and Quiang, 2008; Feng and Wang, 2013), electric power grids (Crucitti et al., 2004), and communication networks (Crucitti et al., 2004; Latora and Marchiori, 2005).

In these studies, resilience is equated with the vulnerability of the engineering system to disruptive events. In particular, the higher the resilience, the lower the vulnerability of the system will be to disruptive events. Two different types of disruptions are distinguished: external and systemic ones (Madni and Jackson, 2009). The first category includes events not depending on the functioning of its components, such as natural disasters, whereas the second includes losses in function, capability or capacity of one or more components that make up the system.

Network theory is the preferred approach to assess resilience of engineering systems. Each component of the system is modelled as a node and links among nodes simulate the physical connections among the components. Disruption affecting one element of the system is modelled as the unavailability of the correspondent node. System resilience is thus measured in terms of the ability of the network to function when nodes are removed or become unavailable (Newman, 2003), focusing in particular on the capacity to maintain the efficiency of the function and the constancy of the system (Leveson et al., 2006).

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

Table 1 summarizes approaches, measures, and antecedents of resilience in ecological, complex, and engineering systems.

Table 1. Resilience in ecological, complex, and engineering systems literature.

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

3 Resilience of industrial symbiosis networks

Studies on resilience of ISNs are quite recent, since the literature has mainly focused on eco-efficiency, i.e., the optimization of the waste flows so as to minimize material and energy consumptions (e.g. Rubio Castro et al., 2011; Montastruc et al., 2013). Scholarly interest in ISN resilience has increased with the growing awareness that the maximization of eco-efficiency approach in design leads to high ISN fragility in the case of disruptive events (Ruth and Davidsdottir, 2009; Chopra and Khanna 2014). Furthermore, recent studies framing ISNs as complex adaptive systems (Chertow and Ehrenfeld, 2012) have also contributed to drive research towards the investigation of ISN resilience, since it is one of the main properties explaining the dynamics of such systems.

Zhu and Ruth (2013) define ISN resilience as the ability of a system to maintain eco-efficient material and energy flows (i.e., the function of the ISN) under disruptions. Similarly, Chopra and Khanna (2014) define resilience as the capability of a system to absorb disruptions, while maintain its structure and function. Both studies adopt a dynamic conceptualization of resilience drawn on the concept of ecological resilience. Similarly to these studies, we consider that an ISN is resilient when characterized by high ability to maintain its function under disruptions. Borrowing from the end-outcome conceptualization developed in complex system literature, we assess the ability of the ISN to maintain its function by measuring the impact of a disruptive event on the performance outcomes of the ISN. A disruptive event is defined as any event able to affect the feasibility conditions of IS relationships, altering the current equilibrium state of the ISN from the technical, economic, and normative points of view (Garner and Keoleian, 1995). From a technical point of view, disruptive events include changes in production volumes of outputs produced by ISN firms (due to both endogenous and exogenous causes), natural disasters resulting in unavailability of production plants, changes in production technologies, operation errors. From an economic point of view, disruptive events are changes in the input purchase costs and waste disposal costs. Finally, changes in normative framework can determine disruptive events such as the impossibility of exchanging specific types of wastes. All these events have negative consequences on the ISN, which can be assessed along three performance dimensions:

- environmental outcomes, e.g., the amount of waste not disposed of in the landfill, the amount of input not purchased from firms outside the network (Sokka et al., 2011; Fraccascia et al., 2014; Park and Behera, 2014);
- economic outcomes, i.e., economic benefits gained by firms involved in symbiotic exchanges (Chertow and Lombardi, 2005; Albino and Fraccascia, 2015);
- structural outcomes, e.g., the number of firms belonging to the network, the number of wastes exchanged, the number of symbiotic relationships in the ISN the volume of flows exchanged in the ISN (Ashton, 2008; Doménech and Davies, 2011).

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

Borrowing from the studies of resilience of ecological systems, we consider diversity and redundancy as critical factors affecting the resilience of an ISN. We frame the ISN as an ecosystem where the firms (organisms) exchange specific wastes. The ecosystem functions correspond to the recycling of wastes among actors (Korhonen, et al. 2001; Korhonen and Baumgartner, 2009).

As to this framing, the diversity of an ISN is defined as the number of wastes exchanged among the firms (Korhonen, 2001a). Accordingly, the higher the number of wastes exchanged within an ISN, the higher the number of functions provided by the network and the higher the resilience of the ISN. In fact, when a waste replacing a given input is eliminated from the ISN, the probability that the considered input could be replaced by another waste increases with the number of different wastes exchanged within the ISN. Hence, the diversity of an ISN as whole positively impacts its resilience.

However, the diversity of any given firm also affects the ISN’s resilience The higher the diversity of the firm, the greater the number of wastes it exchanges with other firms and the greater the number of inputs it replaces with wastes produced by other firms (Korhonen, 2001b). Thus, firms with high diversity have an important role in the ISN: they are in fact able to act as anchor tenants, since they can link themselves to many other firms (Chertow, 1998; Korhonen, 2001b). Making a comparison with ecosystems, such firms correspond to the organisms which have a stronger ecological function for the system and, therefore, play the most important role. For this reason, the firms with high diversity are those potentially able to most affect the performance of the ISN in case of disruptions. Therefore, the greater the diversity of a given firm, the greater its impact on the network performance in case of disruptions, *ceteris paribus*. Hence, firm diversity negatively affects ISN resilience.

In ecosystems, redundancy refers to the presence of different organisms performing the same function for the system. Because even in smaller ecosystems the number of organisms that perform similar functions is plentiful, redundancy is a natural property of such systems. Framing ISNs as ecosystems, redundancy is related to the presence of firms producing the same wastes or requiring the same wastes as inputs. Hence, redundancy is a feature related to each waste produced and used as input. We refer to it as ubiquity of waste. The greater the number of firms producing (requiring) a given waste, the greater the ubiquity of that waste within the ISN. As in ecosystems, ubiquity does not have a negative meaning in ISNs. On the contrary, the lack of ubiquity is a critical problem for ISNs, because it makes the industrial systems extremely vulnerable towards even small systemic and external disruptions. For example, consider the case in which the only firm producing a given waste leaves the network. If the redundancy of the waste is high (i.e., many other firms in the ISN produce the same waste), the firms that were receiving that waste from the company leaving the network will have no difficulty to find a new waste supplier. On the contrary, if the waste considered has low redundancy (i.e., is produced by only few firms within the ISN), companies that were receiving that waste would be forced to purchase the correspondent input from firms outside the network. Therefore, high ubiquity widely contributes to the stabilization of the ISN (Sterr and Ott, 2004). Hence, waste ubiquity is positively associated with ISN resilience.

4 Measuring the resilience of ISNs

4.1 Network-based measurement indices

Previous studies on resilience of ISNs propose measurements using the metrics of network theory. The ISN is framed as a network composed of nodes linked one with each other: each node corresponds to a firm and each link between two nodes represents a symbiotic relationship among them (Zeng et al., 2013; Zhu and Ruth, 2013; Chopra and Khanna, 2014). Disruption is modelled as the removal of a single firm from the network, which is the result of a generic disruptive event. Two different classes of resilience measurements are distinguished: i) those aimed at quantifying the effect of disruptive events on the overall network performance and ii) those aimed at identifying the key firms within the network, i.e., those firms having the highest impact on the network performance in case of their unavailability caused by a disruptive event.

Examples of measurements belonging to the first class are: the remaining number and volume of flows after disruption (Zhu and Ruth, 2013), the number of functioning companies after cascading (Li and Shi, 2015), the number of firms that leave the network (broken nodes) due to unavailability of one company (Zeng et al., 2013). Examples of the second class of measurements are the degree and the betweenness centrality, which are used to identify the key firms within the network (Chopra and Khanna, 2014). The most important firms are those whose corresponding nodes are characterized by the highest values of such network measures.

4.1.1 Limitations

The network theory is a useful methodology to study relationships among components of a system. Thus, this approach is suitable for capturing the domino effect that firm removal can cause on ISN performance outcomes. However, it does not completely capture the real complexity inside an ISN, because it is not able to consider the two main antecedents of ISN resilience, i.e., diversity and ubiquity.

Firstly, firms are not identical, because they can be involved in multiple symbiotic flows and differ in the level of diversity both in input and in output, i.e., in the different number of wastes used and produced. For example, consider an ISN composed of firms A, B, and C and suppose that B uses three different wastes (α, β, γ) produced by A, and C uses only one waste (δ) produced by A. B and C do not exchange any waste one with each other (Figure 1a). Hence, the diversity of B is higher than the diversity of C. Using the classic network theory approach, the removal of either firm B or firm C from the network would cause the removal of just one link (A-B and A-C, respectively) (Figure 1b). Therefore, according to this approach, the removal of firm B or C would have a similar impact on the network's performance. However, if we consider that the two firms have a different value of diversity, we can ascertain that the removal of firm B from the ISN causes the removal of three different waste flows, whereas the removal of firm C causes the removal of only one waste flow. Therefore, the impact of the removal of firm B (having higher diversity) is greater than the removal of C, but this is not captured by the network theory approach.

a b

Figure 1. Exemplar symbiotic flows involving firms with different diversity.

In addition, even the wastes exchanged within an ISN are not equal because of their ubiquity. Different wastes can be produced or used by different numbers of firms. For example, consider the network in Figure 2a, where five firms (A, B, C, D, E) exchange three wastes (α, β, γ). Waste α is produced only by firm A, waste β is produced by firms B and E, and waste γ is produced by firm C. According to the classic network theory approach, the removal of either firm A or firm B would cause the same impact on the network performance: one link would be interrupted and no other firm would be eliminated from the network (Figure 2b). However, if firm A were removed from the ISN, waste α would no longer exchanged within the network and firm C would be forced to purchase the production input in place of the waste from firms outside the ISN. On the contrary, if firm B were to leave the ISN, waste β (having higher ubiquity) would continue to be exchanged within the ISN, because it is also produced by firm E. If the amount of waste β produced were greater than the correspondent input required by firm D, this last firm could continue to not purchase any input from firms outside the network. Hence, in this last case, the impact of the removal of the firm B should be considered lower than the impact of the removal of firm A. The network types of measurement do not capture this information.

a b

Figure 2. Exemplar network involving firms exchanging wastes with diverse ubiquity.

4.2 A new method to measure the resilience of ISNs

4.2.1 The Diversity and Ubiquity indices

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

P is an f x w matrix mapping the *waste production structure*: $P_{ij} = 1$ if firm i produces waste j, otherwise $P_{ij} = 0$. Similarly, **C** is an f x w matrix mapping the *waste use structure*: $C_{ij} = 1$ if firm i uses waste j, otherwise $C_{ij} = 0$. We prefer to build Boolean matrices rather than to map the specific amount of waste exchanged among firms, because many firms consider data on wastes exchanged as confidential and are not prone to revealing this information. Despite this assumption, the effectiveness of the resilience index designed is not reduced.

The network diversity is defined as the number of exchanged wastes among firms. The firm diversity in the production structure is defined as the number of wastes produced by the firm. Similarly, the firm diversity in the use structure is defined as the number of wastes used by the firm in substituting inputs. Each waste exchanged within the ISN is associated with two ubiquity indices: the ubiquity in production and the ubiquity in use. The former is defined as the number of firms that produce that waste whereas the latter as the number of firms that use that waste. The formulas of the diversity and ubiquity indices are shown in Table 2.

Table 2. Diversity and Ubiquity indices.

	Formula	**Description**
ISN Diversity Index		
Diversity of the ISN	$D_{ISN} = w$	Number of exchanged wastes within the ISN
Firm Diversity Indices		
Diversity of firm i producing wastes	$D_i^P = \sum_{j=1}^{w} P_{ij}$	Number of wastes produced by i
Diversity of firm i using wastes	$D_i^C = \sum_{j=1}^{w} C_{ij}$	Number of wastes used by i
Waste Ubiquity Indices		
Ubiquity of waste j produced	$U_j^P = \sum_{i=1}^{f} P_{ij}$	Number of firms producing j

Ubiquity of waste *j* used	$U_j^C = \sum_{i=1}^{f} C_{ij}$	Number of firms using *j*

4.2.2 The firm resilience index

For the generic firm *i*, we define the following two impact indices:

$$\iota_i^P = \frac{1}{D_{ISN}} \sum_{\substack{j=1 \\ s.t.\, U_j^P>0}}^{w} \frac{P_{ij}}{U_j^P} \qquad (1)$$

$$\iota_i^C = \frac{1}{D_{ISN}} \sum_{\substack{j=1 \\ s.t.\, U_j^C>0}}^{w} \frac{C_{ij}}{U_j^C} \qquad (2)$$

where the apex *P* stands for the production structure (i.e. the firm in the role of waste producer) and the apex *C* stands for the use structure (i.e. the firm in the role of waste consumer). Note that the higher the firm diversity ($\sum_{j=1}^{w} P_{ij}$ and $\sum_{j=1}^{w} C_{ij}$), the higher the impact due to the firm removal. The higher the network diversity (D_{ISN}) and the waste ubiquity (U_j^P and U_j^C), the lower the impact due to the firm's removal. In particular, ι_i^P and ι_i^C range from 0 to 1. ι_i^P = 0 when the firm *i* does not produce any wastes and ι_i^P = 1 when the firm *i* is the only waste producer within the ISN[1]. Similarly, ι_i^C = 0 when the firm *i* does not use any wastes and ι_i^C = 1 when the firm *i* is the only firm using wastes within the ISN. A high value of ι_i^P corresponds to a firm that produces a high number of wastes with low ubiquity. The removal of such a firm causes a negative impact on the other firms using its wastes, because these firms do not have any alternative internal supplier in the ISN. Similarly, a high value of ι_i^C corresponds to firm that uses a high number of wastes with low ubiquity. The removal of such a firm is detrimental for its waste-supplier firms: firms that produce that waste can experience great difficulty finding another partner in the ISN using it.

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

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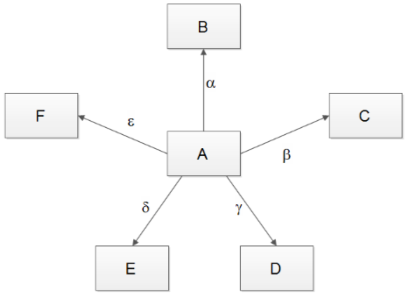
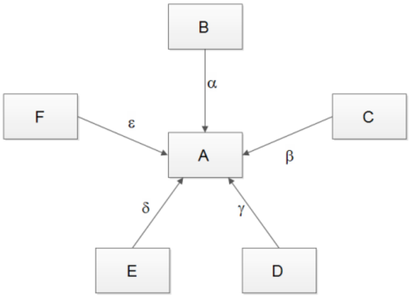
[1] To guarantee that $\frac{1}{D_{ISN}} \sum_{j=1}^{w} \frac{P_{ij}}{U_j^P} = 1$, it is necessary that $\frac{P_{ij}}{U_j^P} = 1 \; \forall j$. This is possible only if $P_{ij} = 1 \; \forall j$ (i.e., firm *i* produces all the wastes exchanged within the ISN) and, at the same time, $U_j^P = 1 \; \forall j$ (i.e., all the wastes have ubiquity = 1). This implies that firm *i* is the only waste producer within the ISN.

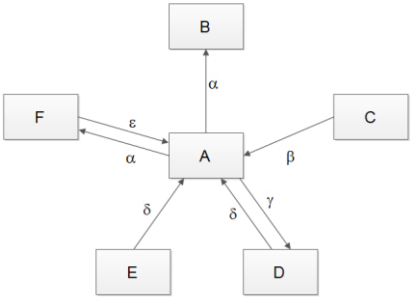
$$\rho_i = 1 - (\iota_i^P + \iota_i^C) \qquad (3)$$

Under the hypothesis that a given firm cannot self-use the wastes that it produces, it can be stated that $0 \leq \rho_i < 1$. In particular, $\rho_i = 1$ is a theoretical condition that cannot be achieved. In this case, firm *i* should produce and use no waste, which means that it is not involved in the ISN. On the contrary, there are the following three cases in which $\rho_i = 0$:

- firm *i* is the only waste producer within the ISN: in this case, $\iota_i^P = 1$ and $\iota_i^C = 0$ (see firm A in Figure 3a);
- firm *i* is the only waste user within the ISN: in this case, $\iota_i^P = 0$ and $\iota_i^C = 1$ (see firm A in Figure 3b);
- firm *i* produces n wastes with $U^P = 1$ and uses $w - n$ wastes with $U^C = 1$ (see firm A in Figure 3c).

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

 a	$\iota_A^P = \frac{1}{D_{ISN}}\left(\frac{P_{A\alpha}}{U_\alpha^P} + \frac{P_{A\beta}}{U_\beta^P} + \frac{P_{A\gamma}}{U_\gamma^P} + \frac{P_{A\delta}}{U_\delta^P} + \frac{P_{A\varepsilon}}{U_\varepsilon^P}\right) = \frac{1}{5}(1+1+1+1+1) = 1$ $\iota_A^C = 0$ $\rho_A = 1 - (\iota_A^P + \iota_A^C) = 1 - (1+0) = 0$
 b	$\iota_A^P = 0$ $\iota_A^C = \frac{1}{D_{ISN}}\left(\frac{C_{A\alpha}}{U_\alpha^P} + \frac{C_{A\beta}}{U_\beta^P} + \frac{C_{A\gamma}}{U_\gamma^P} + \frac{C_{A\delta}}{U_\delta^P} + \frac{C_{A\varepsilon}}{U_\varepsilon^P}\right) = \frac{1}{5}(1+1+1+1+1) = 1$ $\rho_A = 1 - (\iota_A^P + \iota_A^C) = 1 - (1+0) = 0$



c

$$\iota_A^P = \frac{1}{D_{ISN}}\left(\frac{P_{A\alpha}}{U_\alpha^P} + \frac{P_{A\gamma}}{U_\gamma^P} + \right) = \frac{1}{5}(1+1) = \frac{2}{5}$$

$$\iota_A^C = \frac{1}{D_{ISN}}\left(\frac{C_{A\beta}}{U_\beta^C} + \frac{C_{A\delta}}{U_\delta^C} + \frac{C_{A\varepsilon}}{U_\varepsilon^C}\right) = \frac{1}{5}(1+1+1) = \frac{3}{5}$$

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

Figure 3. Exemplar networks with $max\{\rho_i\} = 0$.

5 Applications

We apply our indices to two real ISNs in order to test how they work. The considered ISNs are located in China and in Denmark, respectively. For each network, the resilience indices of the ISN firms are computed. We also compare our results against two types of measurement developed in the literature: one concerning the number of waste flows eliminated in the case of firm unavailability (Zeng et al., 2013; Zhu and Ruth, 2013) and the other concerning the centrality measures (Chopra and Khanna, 2014).

5.1 Jinan City (China)

This first case concerns the ISN located close to the city of Jinan, the capital of Shandong province, the third largest province in China in term of GDP (Dong et al., 2014). The ISN is made up of seven firms and has a star topology. The central node is JIS Corporation, one of the most important enterprises in Jinan: it exchanges twelve different wastes with five firms and the local community. No waste exchange occurs among the other members of the ISN. Figure 4 shows the map of firms involved in the symbiotic exchanges and waste flows among them. Each block corresponds to a firm except for the block on the right, which represents the local community.

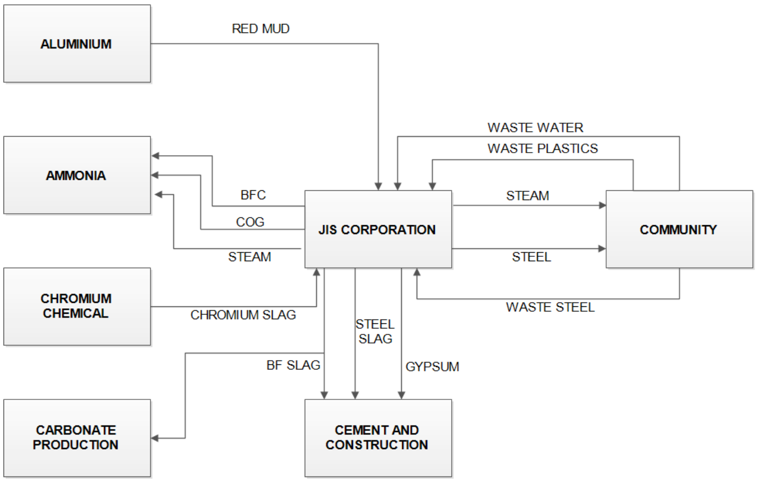
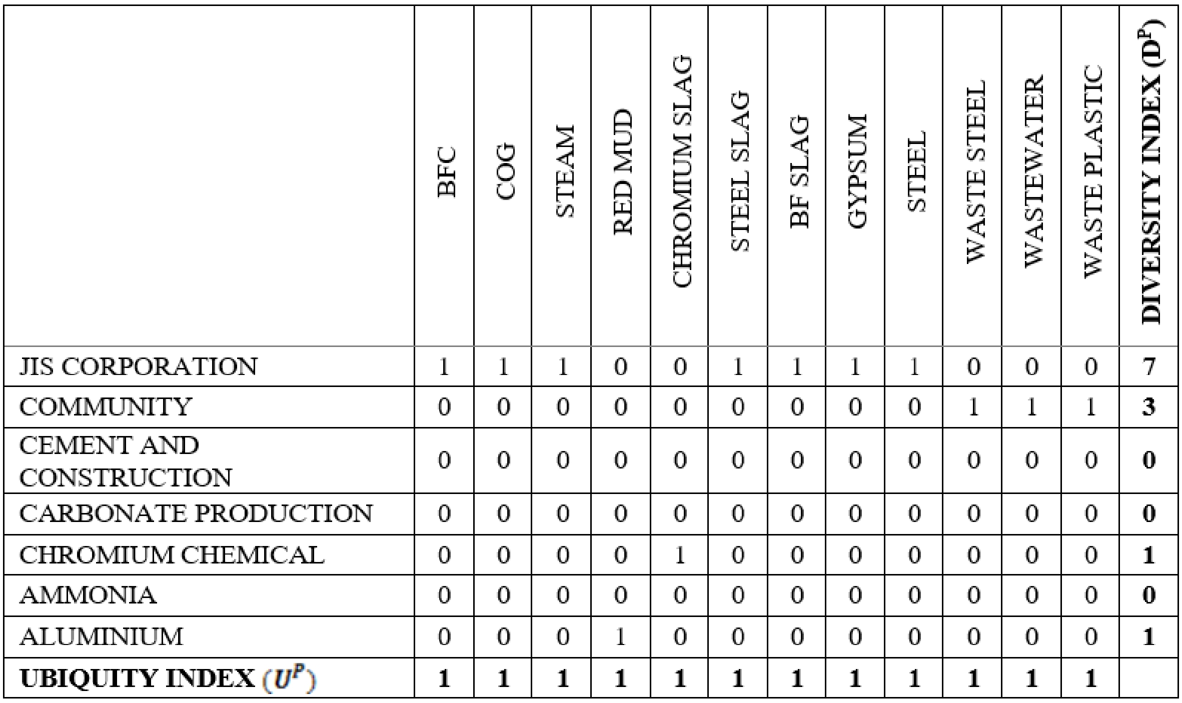


Figure 4. Map of the symbiotic exchanges in Jinan City.

To compute our indices, we first define the ISN waste production structure (P matrix) and the waste use structure (C matrix) (Tables 3 and 4). For each firm and for each waste, the diversity indices and the ubiquity indices are then computed (last row and column of the tables).

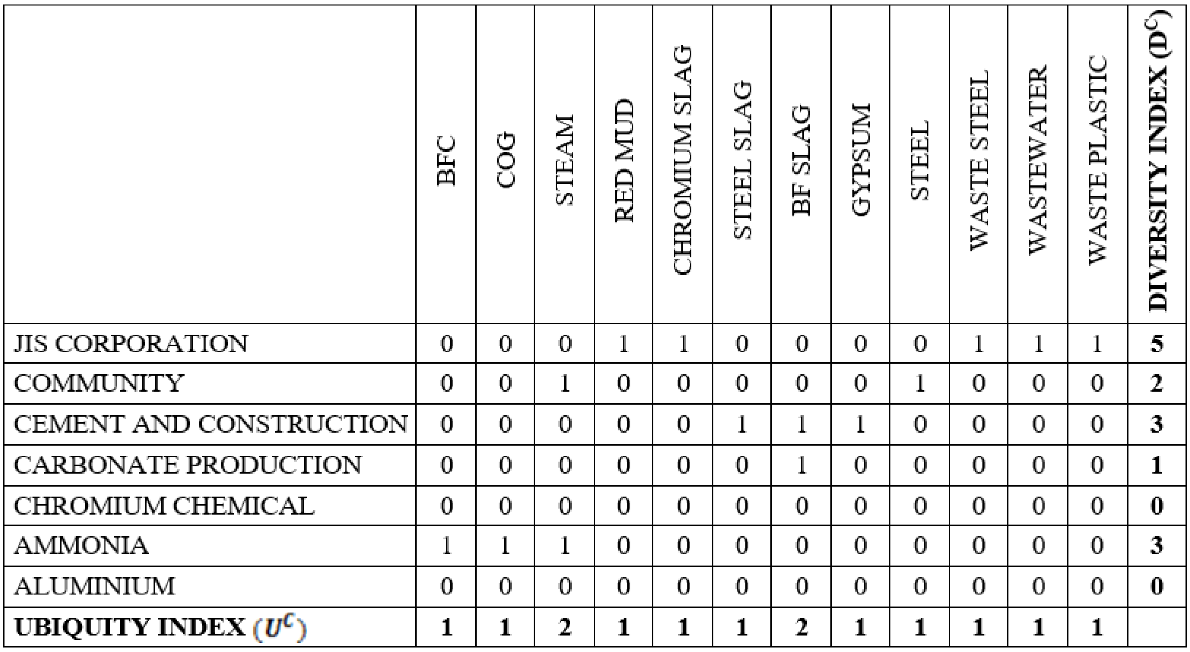
This ISN has the following characteristics. On average each firm produces 1.71 wastes and uses 2 wastes. Firm diversity ranges from 0 to 7 and from 0 to 5 in the production and use structures, respectively. Each waste is on average produced by 1 firm and used by 1.17 firms. In the production structure, all the 11 wastes have the same ubiquity (1), while in the use structure two wastes (steam and BF Slag) have a ubiquity of 2.

Table 3. Waste production structure in Jinan City; firm diversity and waste ubiquity.



	BFC	COG	STEAM	RED MUD	CHROMIUM SLAG	STEEL SLAG	BF SLAG	GYPSUM	STEEL	WASTE STEEL	WASTEWATER	WASTE PLASTIC	**DIVERSITY INDEX (D^P)**
JIS CORPORATION	1	1	1	0	0	1	1	1	1	0	0	0	**7**
COMMUNITY	0	0	0	0	0	0	0	0	0	1	1	1	**3**
CEMENT AND CONSTRUCTION	0	0	0	0	0	0	0	0	0	0	0	0	**0**
CARBONATE PRODUCTION	0	0	0	0	0	0	0	0	0	0	0	0	**0**
CHROMIUM CHEMICAL	0	0	0	0	1	0	0	0	0	0	0	0	**1**
AMMONIA	0	0	0	0	0	0	0	0	0	0	0	0	**0**
ALUMINIUM	0	0	0	1	0	0	0	0	0	0	0	0	**1**
UBIQUITY INDEX (U^P)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 4. Waste use structure in Jinan City; firm diversity and waste ubiquity.



	BFC	COG	STEAM	RED MUD	CHROMIUM SLAG	STEEL SLAG	BF SLAG	GYPSUM	STEEL	WASTE STEEL	WASTEWATER	WASTE PLASTIC	**DIVERSITY INDEX (D^C)**
JIS CORPORATION	0	0	0	1	1	0	0	0	0	1	1	1	**5**
COMMUNITY	0	0	1	0	0	0	0	0	1	0	0	0	**2**
CEMENT AND CONSTRUCTION	0	0	0	0	0	1	1	1	0	0	0	0	**3**
CARBONATE PRODUCTION	0	0	0	0	0	0	1	0	0	0	0	0	**1**
CHROMIUM CHEMICAL	0	0	0	0	0	0	0	0	0	0	0	0	**0**
AMMONIA	1	1	1	0	0	0	0	0	0	0	0	0	**3**
ALUMINIUM	0	0	0	0	0	0	0	0	0	0	0	0	**0**
UBIQUITY INDEX (U^C)	**1**	**1**	**2**	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	

Table 5 shows the indices ι_i^P, ι_i^C and ρ_i for all ISN firms. JIS Corporation is characterized by the highest values of both ι_i^P and ι_i^C. Furthermore, it has $\rho = 0$. This means that, in case of disruptive events causing the removal of JIS Corporation from the network, the ISN as a whole will be subjected to disruption. In fact, this case is conceptually analogous to that depicted in Figure 3c. Community, Cement and Construction, and Ammonia exhibit a moderate level of resilience (0.625, 0.7917, and 0.7917, respectively). Chromium Chemical, Aluminium, and Carbonate Production show high resilience indices.

Table 5 also shows the values of the centrality measures (degree centrality and betweenness centrality[2]) and the indices concerning the number of waste flows eliminated in case of firm removal[3].

Table 5. Resilience measurements: Resilience indices, impact, and centrality measures in Jinan.

	RESILIENCE INDICES			**IMPACT ON THE NETWORK STRUCTURE**		**CENTRALITY MEASURES**	
	ι_i^P	ι_i^C	ρ_i	Number of different waste flows eliminated	Number of waste flows eliminated	Degree centrality	Betweenness centrality
JIS CORPORATION	0.5833	0.4167	**0**	12	14	6	15
COMMUNITY	0.2500	0.1250	**0.6250**	5	5	1	0
CEMENT AND CONSTRUCTION	0	0.2083	**0.7917**	3	3	1	0
AMMONIA	0	0.2083	**0.7917**	3	3	1	0
CHROMIUM CHEMICAL	0.0833	0	**0.9167**	1	1	1	0
ALUMINIUM	0.0833	0	**0.9167**	1	1	1	0
CARBONATE PRODUCTION	0	0.0417	**0.9583**	1	1	1	0

A comparison of the resilience index with the other measurements shows that some differences exist. All indices agree that the most critical firm is JIS Corporation. However, only the resilience index is able to show that JIS Corporation can cause the disruption of the ISN as a whole since the critical value $\rho = 0$ is reached. For the other firms, the different

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[2] Degree centrality of a point in a graph is the count of the number of other points that are adjacent to it.
Betweenness centrality of a point is defined as $C_B(n_i) = \sum_{j \neq k} \frac{g_{jk}(n_i)}{g_{jk}}$, where $g_{jk}(n_i)$ is the number of shortest paths connecting the points *j* and *k* passing through *i*, and g_{jk} is the number of geodesics connecting *j* and *k*.

[3] The *number of different waste flows eliminated* is computed by counting the number different wastes a firm exchanges.
The *number of waste flows eliminated* is computed by counting the number of the waste flows from and to the firm. For instance, if a firm exchanges one waste with two different firms, the *number of different waste flows eliminated* is equal to one whereas the *number of waste flows eliminated* is equal to two.

indices provide contrasting information. In fact, based on the centrality measures all the firms (except JIS Corporation) have the same level of resilience. The measures of impact on the network structure show that Community, Cement, and Ammonia are characterized by lower levels of resilience than Chromium Chemical, Aluminum, and Carbonate Production. Our resilience index confirms this but also captures the slight differences between Chromium Chemical, Aluminum, and Carbonate Production. To illustrate this point, consider Carbonate Production and Chromium Chemical. Both these firms have total diversity ($D^P + D^C$) equal to 1, because they are involved in exchanging only one waste flow. In particular, Carbonate Production only uses the BF slag produced by JIS Corporation, whereas the Chromium Chemical only provides chromium slag to JIS Corporation (Figure 4). The ubiquity of BF slag is 2, i.e. BF slag is also used by another firm (Cement and Construction), whereas the ubiquity of chromium slag is 1. Since Chromium Chemical exchanges a less ubiquitous waste and both firms have the same diversity, Chromium Chemical has a higher impact than Carbonate Production. In fact, if Chromium Chemical is removed from the ISN, JIS Corporation can no longer receive chromium slag from any other firm of the ISN and it will be forced to purchase the correspondent input from outside the network. Instead, if Carbonate Production is removed, JIS Corporation can still supply the BF slag to Cement and Construction not having the need to dispose the waste in the landfill. Hence, our resilience proves to perform better than the benchmarks.

5.2 Kalundborg (Denmark)

The second case analyzed concerns the ISN in Kalundborg, one of the world’s best-known ISNs. The network has been developing since 1961, as the result of an evolutionary process in which a small number of independent by-product exchanges have gradually evolved into a complex web of symbiotic interactions among several firms located within the Kalundborg industrial area and the local municipality (Ehrenfeld and Gertler, 1997; Jacobsen, 2006).

The network involves seventeen firms exchanging fourteen different wastes among them. Figure 5 shows the map of the waste exchanges within the ISN. Each block corresponds to one firm, except for the “municipality” block which stands for the local community.

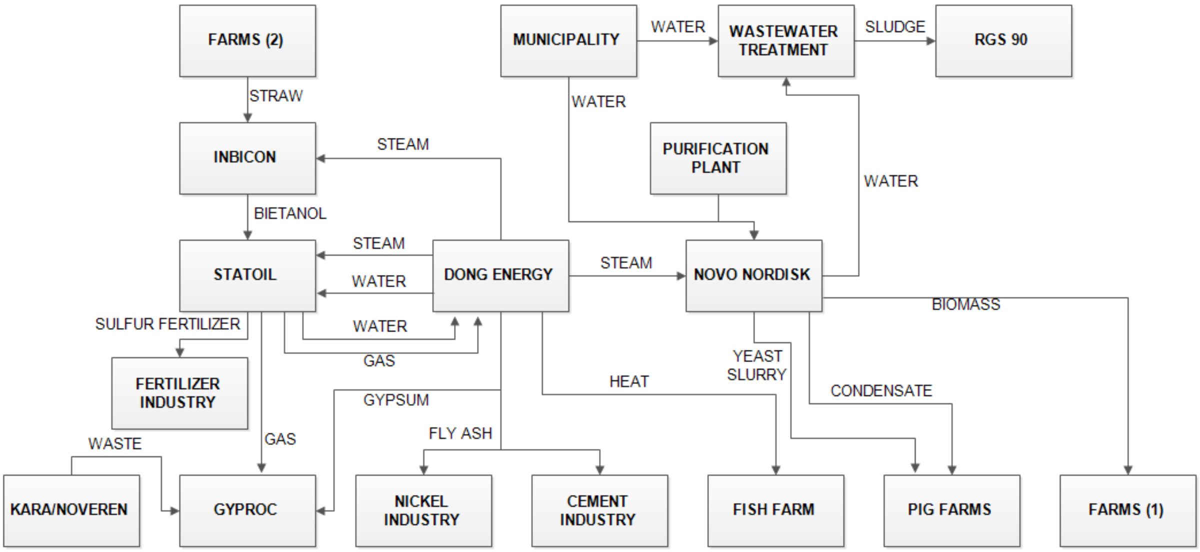
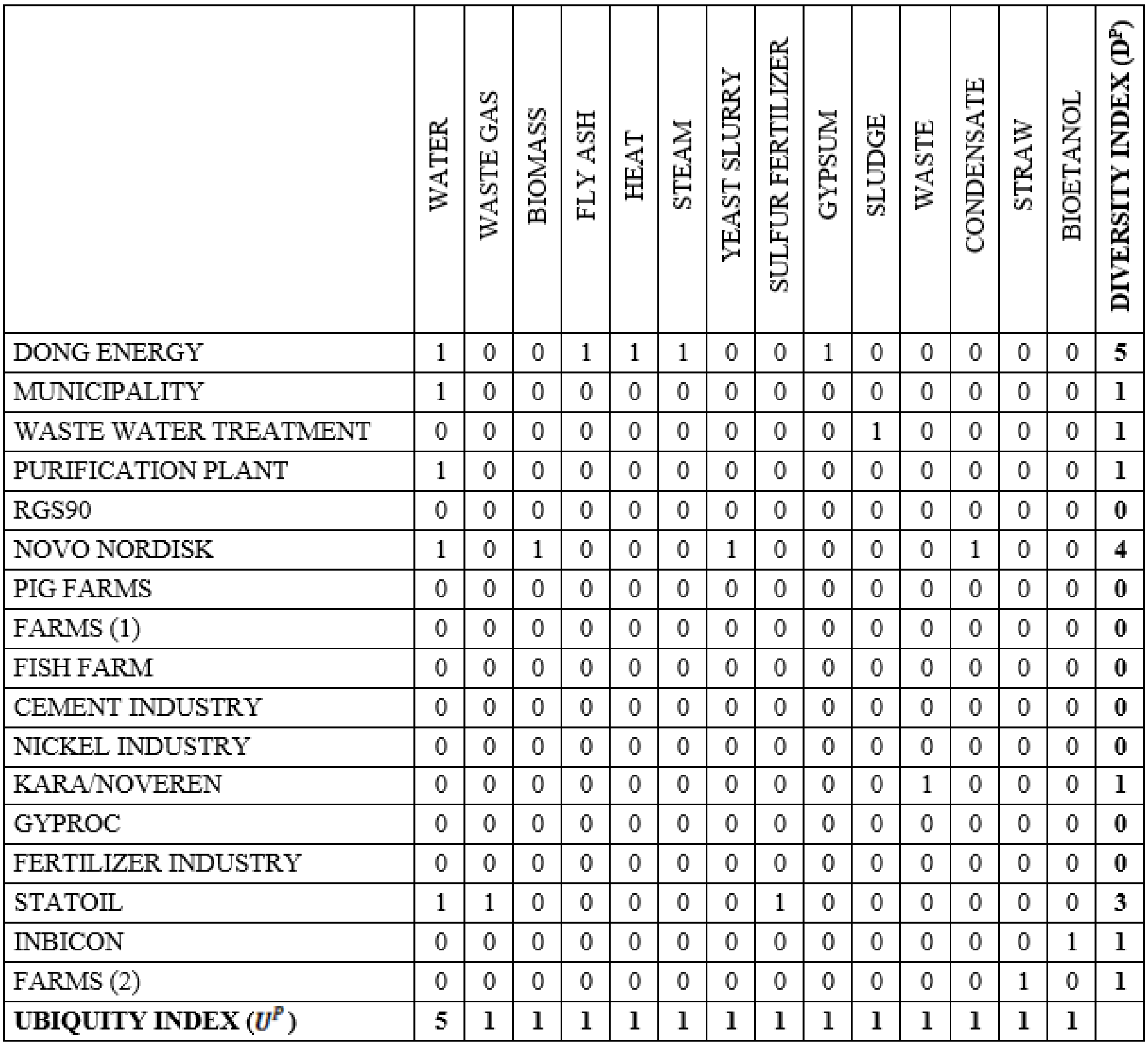


Figure 5. Map of the symbiotic exchanges in Kalundborg.

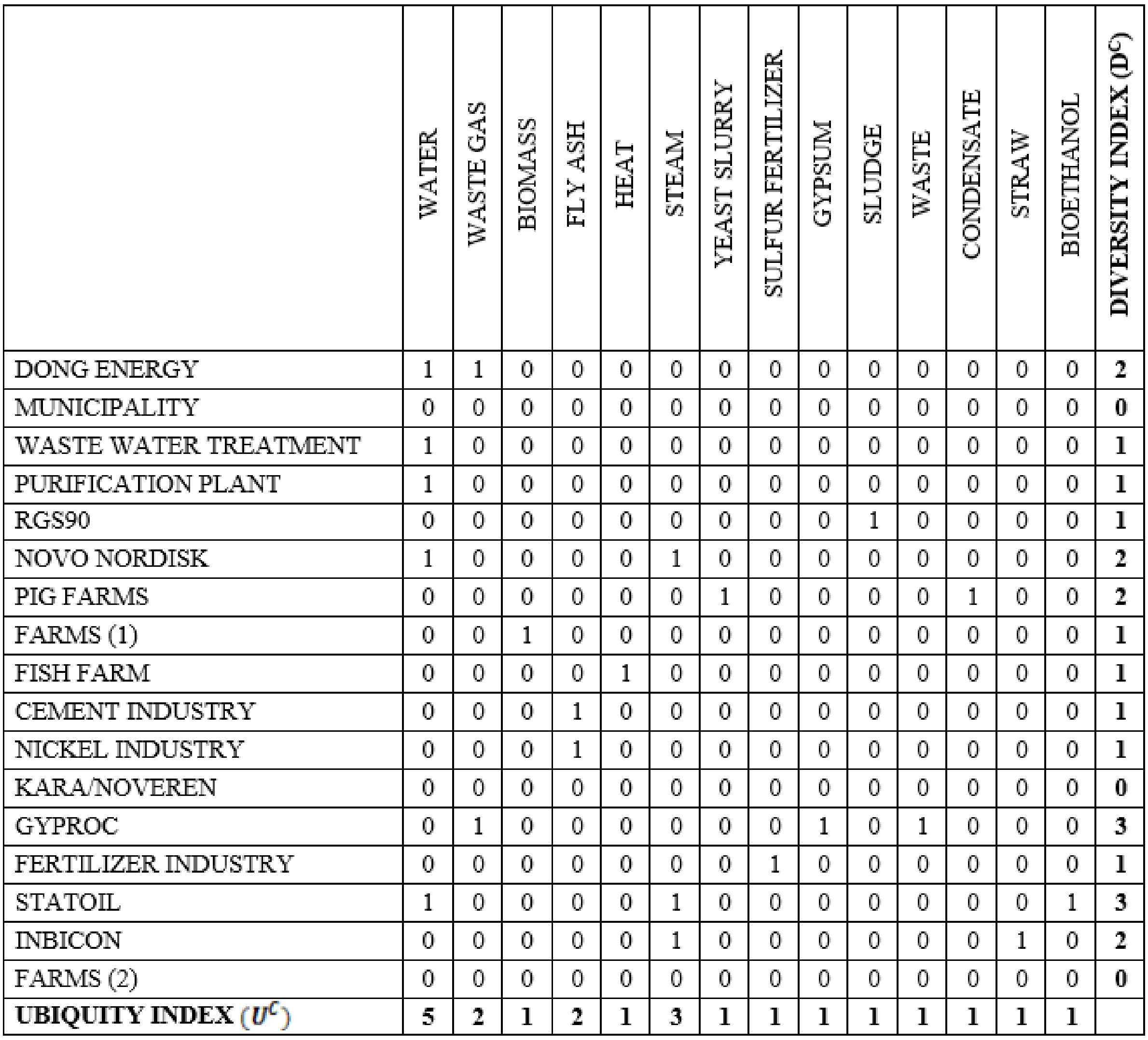
Matrices P and C mapping the waste production and use structures are shown in Tables 6 and 7, respectively. They are used to compute both the firm diversity and the waste ubiquity indices (see last row and column in Tables 6 and 7). The firms produce on average 1.06 different wastes and use 1.29 different wastes. In particular, the firm diversity index ranges from 1 to 5 and from 1 to 3 in the production and use structures, respectively. On average each waste is produced by 1.29 firms and is used by 1.57 firms. In the production structure the waste ubiquity is 5 for the water and 1 for all the other wastes. In the use structure water has ubiquity equal to 5, steam equal to 3, waste gas and fly ash 2, and the remaining wastes 1.

Table 6. Waste production structure in Kalundborg; firm diversity and waste ubiquity.



	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	SLUDGE	WASTE	CONDENSATE	STRAW	BIOETANOL	**DIVERSITY INDEX (D^P)**
DONG ENERGY	1	0	0	1	1	1	0	0	1	0	0	0	0	0	**5**
MUNICIPALITY	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
WASTE WATER TREATMENT	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
PURIFICATION PLANT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
RGS90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
NOVO NORDISK	1	0	1	0	0	0	1	0	0	0	0	1	0	0	**4**
PIG FARMS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FARMS (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FISH FARM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
CEMENT INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
NICKEL INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
KARA/NOVEREN	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
GYPROC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
FERTILIZER INDUSTRY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
STATOIL	1	1	0	0	0	0	0	1	0	0	0	0	0	0	**3**
INBICON	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**
FARMS (2)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
UBIQUITY INDEX (U^P)	**5**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 7. Waste use structure in Kalundborg; firm diversity and waste ubiquity.

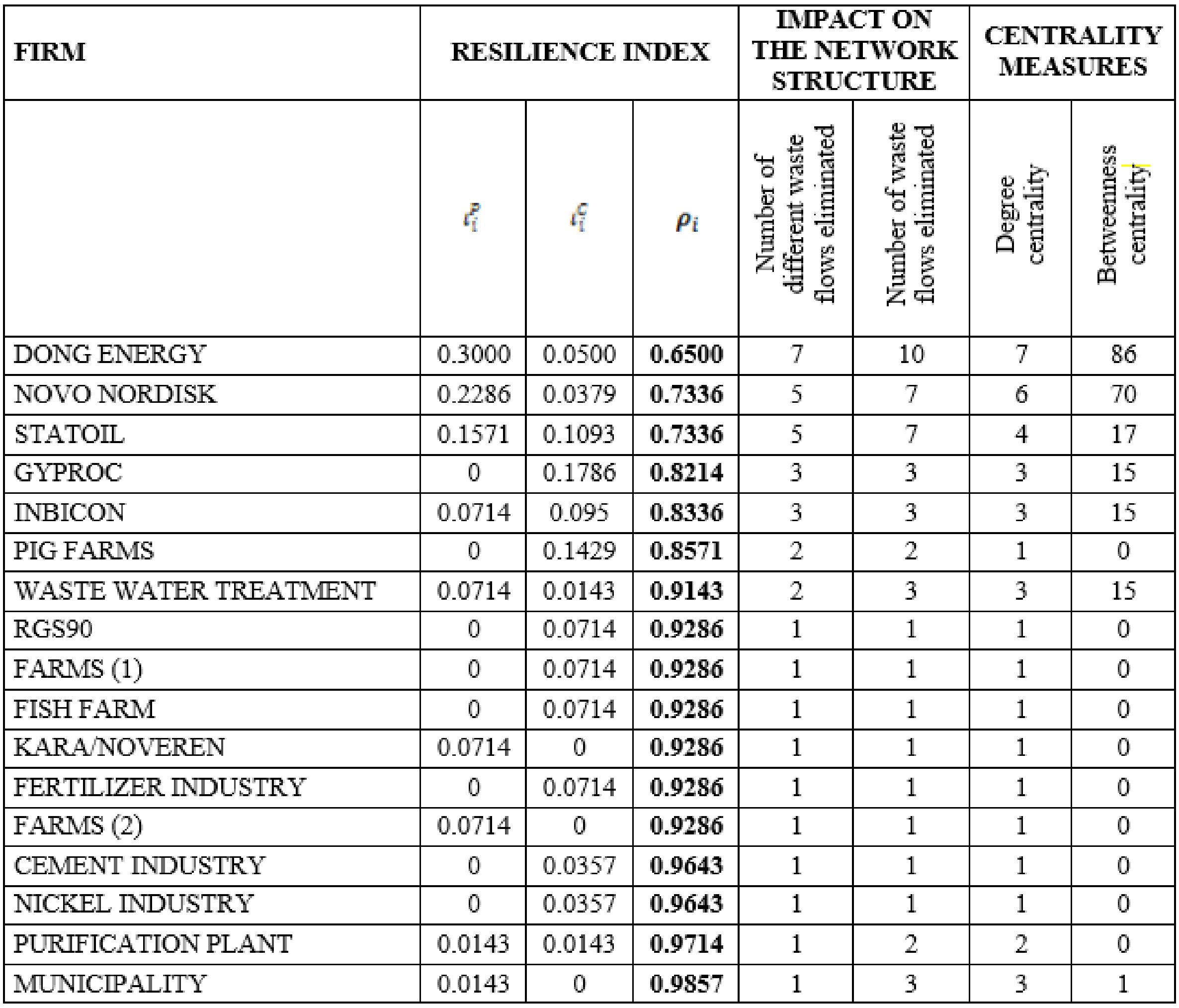


	WATER	WASTE GAS	BIOMASS	FLY ASH	HEAT	STEAM	YEAST SLURRY	SULFUR FERTILIZER	GYPSUM	SLUDGE	WASTE	CONDENSATE	STRAW	BIOETHANOL	**DIVERSITY INDEX (D^C)**
DONG ENERGY	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**2**
MUNICIPALITY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
WASTE WATER TREATMENT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
PURIFICATION PLANT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
RGS90	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
NOVO NORDISK	1	0	0	0	0	1	0	0	0	0	0	0	0	0	**2**
PIG FARMS	0	0	0	0	0	0	1	0	0	0	0	1	0	0	**2**
FARMS (1)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
FISH FARM	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**
CEMENT INDUSTRY	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
NICKEL INDUSTRY	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
KARA/NOVEREN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
GYPROC	0	1	0	0	0	0	0	0	1	0	1	0	0	0	**3**
FERTILIZER INDUSTRY	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**
STATOIL	1	0	0	0	0	1	0	0	0	0	0	0	0	1	**3**
INBICON	0	0	0	0	0	1	0	0	0	0	0	0	1	0	**2**
FARMS (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
UBIQUITY INDEX (U^C)	**5**	**2**	**1**	**2**	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	

Table 8 shows for each firm the resilience index, the centrality measures, and the number of waste flows eliminated. The resilience index ranges from 0.65 to 0.9857. Dong Energy, Statoil, and Novo Nordisk are the most critical firms in case of disruptive events. No firm is characterized by $\rho = 0$. Accordingly, no firm is able to drastically affect the survival of the ISN as a whole. This ISN is therefore characterized by a higher resilience than the previous one.

The number of waste flows ranges from 1 to 10. The degree centrality moves from 1 to 7 and the betweenness centrality from 0 to 86.

Table 8. Resilience measurements: resilience indices, impact, and centrality measures in Kalundborg.



FIRM	RESILIENCE INDEX			IMPACT ON THE NETWORK STRUCTURE		CENTRALITY MEASURES	
	ϵ_i^P	ϵ_i^C	ρ_i	Number of different waste flows eliminated	Number of waste flows eliminated	Degree centrality	Betweenness centrality
DONG ENERGY	0.3000	0.0500	**0.6500**	7	10	7	86
NOVO NORDISK	0.2286	0.0379	**0.7336**	5	7	6	70
STATOIL	0.1571	0.1093	**0.7336**	5	7	4	17
GYPROC	0	0.1786	**0.8214**	3	3	3	15
INBICON	0.0714	0.095	**0.8336**	3	3	3	15
PIG FARMS	0	0.1429	**0.8571**	2	2	1	0
WASTE WATER TREATMENT	0.0714	0.0143	**0.9143**	2	3	3	15
RGS90	0	0.0714	**0.9286**	1	1	1	0
FARMS (1)	0	0.0714	**0.9286**	1	1	1	0
FISH FARM	0	0.0714	**0.9286**	1	1	1	0
KARA/NOVEREN	0.0714	0	**0.9286**	1	1	1	0
FERTILIZER INDUSTRY	0	0.0714	**0.9286**	1	1	1	0
FARMS (2)	0.0714	0	**0.9286**	1	1	1	0
CEMENT INDUSTRY	0	0.0357	**0.9643**	1	1	1	0
NICKEL INDUSTRY	0	0.0357	**0.9643**	1	1	1	0
PURIFICATION PLANT	0.0143	0.0143	**0.9714**	1	2	2	0
MUNICIPALITY	0.0143	0	**0.9857**	1	3	3	1

A comparison between the results of the resilience index, the impact indices on the number of waste flows eliminated, and the centrality measures confirms that our index is more effective in measuring resilience. For example, Fish Farm and Cement Industry, which have the same level of resilience on the basis of both the centrality measures and number of waste flows controlled, are different using our the resilience index (ρ = 0.9286 and 0.9643 for Fish Farm and Cement Industry, respectively). In fact, although both firms have the same diversity (neither produces any waste and both only use one waste), they differ in the average ubiquity of the wastes used. Fish Farm uses heat, which is not used by any other firm ($U^C = 1$), while Cement Industry uses fly ash, which is used also by Nickel Industry ($U^C = 2$). This condition implies that even if Cement Industry is removed from the ISN, the fly ash produced by ISN firms will continue to be recovered within the network. On the contrary, if Fish Farm is removed from the network, heat will no longer be recovered by any firm.

Even more emblematic is the case of Waste Water Treatment (WWT) and Pig Farms. Both centrality measures and measures of impact suggest that WWT is more critical than Pig

Farms, since WWT is connected with three firms whilst Pig Farms is only linked with Novozymes. Conversely, based on our resilience index, we obtain that WWT is less critical than Pig Farms. WWT receives water from Municipality and Novozymes and provides sludge to RGS 90. Pig Farms uses yeast slurry and condensate from Novozymes. All these wastes have ubiquity equal to one except for water, whose ubiquity is 0.20. Therefore, although WWT is more connected and controls a higher number of waste flows than Pig Farms, it exchanges less exclusive wastes (i.e. wastes having a higher than average ubiquity), than those exchanged by WWT. For these reasons, WWT is less critical in case of disruptive events than Pig Farms.

6 Discussion and Conclusions

The constantly increasing impact that the disruptive events have on the sustainability of ISNs demonstrates that IS should receive recognition for having brought resilience to the fore as a core concept. The need to design resilient ISNs requires that the key antecedents of resilience be identified and that proper ways to measure it be defined. We provide a contribution to this line of research by offering a new conceptualization of resilience in ISNs, reviewing the studies analyzing resilience of ecological, complex, and engineering systems. In doing so, we differ from previous studies on resilience in ISNs, which have mainly conceptualized ISN resilience in terms of vulnerability and adopted network measures to assess it.

Our conceptualization of resilience is mainly drawn from ecological systems literature and focuses on the antecedent role of diversity and ubiquity. We provide a conceptualization of both variables in the ISN context and build a resilience index depending on both of them. Network diversity refers to the number of exchanged wastes within the ISN whereas firm diversity refers to the number of diverse wastes a firm produces and uses. Waste ubiquity refers to the number of firms that produce and use that waste. At equal firm diversity, a firm’s resilience index is higher, the greater the ubiquity of the wastes that the firm exchanges. At equal waste ubiquity, the higher a firm’s diversity, the lower its resilience index. Resilience is also affected by network diversity: the higher it is, the greater the capacity of the ISN to reorganize its waste flows in case of disruption. Thus, firms producing and using a great number of wastes with low ubiquity are critical for ISN sustainability. In particular, a resilience index equal to zero identifies firms which are highly critical for an ISN’s sustainability. The removal of these firms causes the collapse of the entire ISN. In contrast, the removal of a firm producing or using a low number of wastes with high ubiquity, the network can easily reorganize the structure of waste flows.

We analyzed two different case studies. These case studies were useful to test the application of the proposed indices to real analysis. They also served to show the superior power of the resilience index proposed, compared to the classical network-based ones. In this regard, both the cases highlighted the limits of the measurement methods commonly adopted in the literature to evaluate the vulnerability of ISNs to firm removal. We showed that the centrality measures can only capture the symbiotic relationship among different companies, but not take into account the different number of wastes exchanged among them. Our resilience index also proved better than the benchmark indices computing the number of waste flows eliminated in case of firm removal. In fact, we showed that the benchmark indices cannot distinguish between common and exclusive wastes, considering them in the same way. Our index overcomes both these drawbacks, being designed to include not only the effect of the number of wastes exchanged (firm diversity), but also that of their ubiquity.

Our resilience index has additional advantages compared with traditional measurements. It is simpler to compute, particularly compared with the centrality measures. Moreover, since we recognized that firms having a resilience index equal to zero are very dangerous for the ISN survival in the case of their removal, our resilience index also proves very quick in identifying networks with very high vulnerability.

Our study confirms and extends the literature on ISN resilience. Framing the ISN as an ecosystem, we identified three fundamental drivers of ISN resilience: the diversity of the network, the diversity of individual firms, and the ubiquity of the wastes exchanged. As emerged by comparing the case-study analyses, we have confirmed that network topology affects ISN resilience. In fact, we found that the resilience of Jinan City's ISN showing a star topology is lower than that of Kalundborg's ISN having a meshed structure. We explain this outcome by means of the influence that the network topology plays on firm diversity and waste ubiquity and, as a consequence, on resilience. Consider an ISN with a star topology (like Jinan City or, more in general, like the ISNs depicted in Figure 3), where the central firm exchanges wastes with all the other firms, among which no exchanges occur. This network structure determines two conditions: i) the central firm has much higher diversity than the other firms; ii) all wastes produced by the central firm have ubiquity equal to one in the production $(U_j^P = 1 \ \forall j)$, at the same time, all wastes used by the central firm have ubiquity equal to one in the use $(U_j^C = 1 \ \forall j)$. According to our conceptualization, such conditions negatively influence resilience. Furthermore, this particular structure leads to the very critical situation, whereby a resilience index equal to zero is reached. This means that the ISN is highly vulnerable. Consider now an ISN presenting a meshed network topology characterized by waste flows spread among firms (like the Kalundborg's ISN). In such networks, since waste flows are spread among firms, it is unlikely that only one firm produces or uses all the wastes exchanged. Even in the case where a firm has a high diversity, since the wastes that it exchanges are produced and used also by other firms, their ubiquity is high. Thus, this structure, in positively influencing waste ubiquity, is associated with high resilience.

Finally, the results of our study contribute to the design of sustainable ISNs. In order to ensure that the network is characterized by high resilience, we suggest designing ISNs with high network diversity, characterized by firms having low diversity, and exchanging wastes with high ubiquity. We recommend avoiding that only few firms exchange a high number of wastes, i.e. that a small number of firms have a much greater diversity than all the others. We can also suggest which strategies to follow for increasing the resilience in existing ISNs. Once the most critical firms in the ISN have been identified, the lower resilience index could be increased by improving network diversity, i.e. the number of exchanged wastes within the ISN, and/or the waste ubiquity, i.e. the number of firms producing and using such wastes. Both these strategies can be implemented adding new firms within the ISN.

The study presents some limits. Our resilience indices are designed to measure only the impact due to firm removal from the network, which is probably the most critical disruption able to affect ISNs. However, other, less dangerous, disruptive events can occur. Although events such as changes in production levels, equipment faults, and operation errors usually have a lower impact on the network functioning than firm removal, they may occur with higher frequency. In addition, our indices do not take into account the amount of the exchanged wastes nor their economic value. New indices built to analyze these situations are a subject for future research. This should be also devoted to the analysis of further determinants of ISN resilience for example those suggested by the review of the complex systems resilience. This will contribute to develop an overarching conceptualization of ISN resilience.

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