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Resilience Study Applied in Eco-Industrial Parks

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Abstract

An Eco-Industrial Park (EIP) is a community of businesses that seeks to reduce the global impact through material sharing.

Even though an EIP presents an environmental improvement when compared with a set of stand-alone industrial plants, the established connections among the industrial participants can propagate failures, and become in a source of risk. For this reason, this work proposes an indicator to follow the resilience of EIPs, which is constructed to be applied on the design phase of eco-industrial parks, by means of an optimization problem. This indicator is based on two aspects of an industrial network: its topology and its operative flexibility. These aspects are measured by two respective sub-indicators, Network Connectivity Index (NCI) and Flow adaptability index (ϕ). Both sub-indicators are integrated to compose a global resilience indicator.

Finally, we apply the resilience indicator over five illustrative cases in order to analyze its applicability, obtaining consistent results.

Keywords: Indicator; Resilience; Security; Eco-industrial parks.

1. Introduction

An Eco-industrial park (EIP) is a community of businesses located together on a common property, sharing materials, energy, or infrastructures. An EIP is motivated by the economic, environmental, and social improvements achieved through the collaboration among the firms within the park (Boix et al. (2015)). These relationships foster the implementation of Industrial Symbiosis (IS), which seeks to transform wastes, by-products or products of a firm into inputs of another one taking advantages of their own connections (Chertow (2000)).

An optimization problem can be formulated to design an EIP (Boix et al. (2015)). This formulation can back up decisions during the design phase of an EIP, formalizing the industrial planning to make the industrial development more sustainable.

In this context, there are several works regarding to propose a mathematical formulation in order to design an EIP (Boix et al. (2015)). Even though EIPs are largely studied in the literature, they suffer of reluctance from industries. Indeed, the potential industrial participants are often hard to convince due to security issues when connecting processes, because failures are also propagated through a network.

In computer science, a security or resilience factor is considered when defining a network so as to reduce its vulnerability. This measure takes into account the topology of the network, quantifying the damage done to the whole network when the most critical element (e.g. the element with the maximum number of connections) is removed (Matta et al. (2014)).

In the context of EIP design, if we obtain an optimal configuration on the basis of the three sustainability dimensions, the question is what would happen if a participant is removed from the park. A pending issue in this field is to plan the connections of a single plant considering the stability of the other participants and their flow requirements, specially during failures within the network. In consequence, a new objective can be defined during the design phase to improve the security of the network by increasing its resilience.

Chopra and Khanna (2012) propose four metrics to apply over EIPs, all of them sustained on a network theory approach (Chopra and Khanna (2012)). The goal of these metrics is to measure the impact of a disruptive event of a park, focusing on their most affected nodes. These metrics are related with two aspects of the resilience of an industrial network: its connectivity and its efficiency. The first one establishes how necessary is to use a node to connect with others, and the second one, measures the changes in the efficiency of the park when a disruptive event occurs. Even though the authors obtain good results when apply these measures over an example, they propose to work on the resilience or adaptability of a network. In this context, an important lack of this metric is the quantification of the minimum performance of the network to be functional.

The novelty of this work is to create an indicator to measure the resilience of an industrial network based on its topology and operative aspects. The main difference with previous efforts is the orientation of the proposed indicator to operative changes after a disruption. The construction of this indicator relies on graph representation and is developed to be used in an optimization problem oriented to design an eco-industrial parks. To illustrate the use of this index, we apply it over five application cases. Accordingly, the objectives of this paper are to propose a resilience metric over EIPs and to illustrate its use.

2. Resilience indicator

We adopt the definition from Fiksel (2003), where the authors define this concept as "the capability of the system to absorb disruptions before it changes its properties that control its functionality. This property allows an IS network to endure the impact of unforeseen event".

In this work, we consider a disruptive event as when a participant interrupts completely its activity. Therefore, if a disruptive event involves a participant, its associated connections (edges) disappear. In addition, since the network must continue operating, the other participants must modify the magnitude of their inputs and outputs to compensate the losses without important changes in its configuration (e.g. entering of a new participant).

Therefore, a resilience indicator must be focused on two aspects: (i) if the connections in the park are enough to withstand a disruptive event, and (ii) if the remaining participant can compensate the lost flows when a firm interrupts its activity.

For this purpose, the proposed resilience indicator measures two aspects of a network through the combination of two metrics: Network Connectivity Index (NCI) and Flow adaptability index (ϕ). The first one measures the number of connections among participants and the second one measures the capacity of the participants of the network to compensate the flow demand when a firm suffers a disruptive event.

To define the metrics, and to support its application the design phase of EIP though an optimization problem, we use a graph representation of the park (Aviso et al. (2010)). Accordingly, each participant of the park is represented by a node, and the connections by oriented edges. Based on this representation, we define the following terms and sets:

- N: Set of park participants.
- C: Number of connections among park participants.
- n: Number of participants in the network.
- IN_k: Set of participants that have an input into $k \in N$.
- OUT_k: Set of participants that have an output from $k \in N$.
- $Q_i^{min,in}$: Minimum input needed capacity for the participant $i \in N$ to operate.
- $Q_l^{max,in}$: Maximum input capacity of the participant $l \in N$.
- $Q_m^{max,out}$: Maximum output capacity of the participant $m \in N$.
- $F_{i,j}$: Magnitude of the flow between $i \in N$ and $j \in N$.
- ϕ_k: Flow sensitivity of the participant $k \in N$ in a network.
- NCI: Network Connectivity Index of a park.
- ϕ: Flow sensitivity of a park.

The goal of NCI is to measure if there are enough connections in a network to endure a possible disruption. In this sense, the more connections in the park, the better for the stability of the network, and NCI increases its value. The risk of isolation of the participants decreases with the grow of NCI.

The general idea of this metric is to set a maximum and a minimum number of connections of the network, and to establish its level of connectivity according to these values. We define the maximum number of connections as the maximum possible number of edges among participants (Eq. (1)); and the minimum number of connections, as the minimum number of edges to maintain the identity of the park (Eq. (2)). We assume that an EIP maintains its identity when each node has one connection at least. We define the corresponding NCI value associated to the maximum and minimum number of connections of a park. Then, if the network has C_m^{max} connections, $NCI(C_n^{max}) = 1$. Otherwise, if the network has C_m^{min} connections, $NCI(C_n^{min}) = 0$. With these values, and to simplify the calculation, we establish a linear function between both cases (Eq. (3)).

$$C_n^{max} = \frac{n(n-1)}{2} \quad (1) \qquad C_n^{min} = n - \left\lfloor \frac{n}{2} \right\rfloor \quad (2) \qquad NCI(n,C) = \frac{2(C - n + \lfloor \frac{n}{2} \rfloor)}{n^2 - 3n + 2\lfloor \frac{n}{2} \rfloor} \quad (3)$$

On the other hand, the goal of ϕ is to quantify the necessary flow to sustain the operation of the park by modifying the remaining flows after a disruption. In this sense, if the flow magnitudes in the park can change to compensate the activity interruption of a firm, the other participants can maintain their operation. Therefore, ϕ measures the flexibility of the park when a participant interrupts its activity and to determine if the other members can compensate this event through changes in their inputs and outputs.

Let k be the reference to a specific material being shared in the network. To determine the capacity of the park participants to absorb disruptive events (changes in the network), we consider that every plant has a security range for inlets and outlets, i.e. a maximum and minimum flow to operate. We define the maximum inlet and outlet capacity of a participant $k \in N$ as $Q_k^{max,in}$ and $Q_k^{max,out}$, and the minimum inlet capacity of a participant $k \in N$ as $Q_k^{min,in}$. Since we need to measure the change over the park when a participant interrupts its activity, we define the "total lack of flows related to a disruption in k", $\mathbb{L}_k$, as:

$$\mathbb{L}_k = \sum_{i \in OUT_k} \max\left\{0, Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i} - \sum_{m \in IN_i; m \neq k} \left(Q_m^{max,out} - \sum_{w \in OUT_m; w \neq k} F_{m,w}\right)\right\}$$
$$+ \sum_{j \in IN_k} \max\left\{0, F_{j,k} - \sum_{l \in OUT_k; l \neq k} \left(Q_l^{max,in} - \sum_{v \in IN_l; v \neq k} F_{v,l}\right)\right\} \qquad \forall k \in N \quad (4)$$

As NCI, we define the worst and the best cases to compensate the loosed flow, and establish a linear function between them. The worst case is defined when each participant is operating at full capacity: $\mathbb{L}_k$ is maximum. On the other hand, the best case is when the network can totally compensate the activity interruption of their participants: $\mathbb{L}_k$ is minimum. Establishing both cases, we define ϕ_k for the network affected by the interruption in the activity of the participant k (Eq. (5)). Accordingly, if the park is working at the worst case, $\phi_k(\mathbb{L}_k^{max}) = 0$; and if the park is working at the best case, $\phi_k(\mathbb{L}_k^{min}) = 1$. Finally, we apply ϕ_k over each participant and calculate its average, in order to simplify the calculation, obtaining the Flow adaptability index ϕ of the whole park (Eq. (6)).

$$\phi_k(\mathbb{L}_k) = 1 - \frac{\mathbb{L}_k}{\sum_{j \in IN_k} F_{j,k} + \sum_{i \in OUT_k} Q_i^{min,in}} \quad k \in N \qquad (5)$$

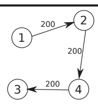
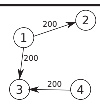
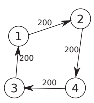
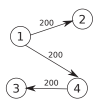
$$\phi = \frac{1}{n} \sum_{k \in N} \phi_k \qquad (6)$$

Finally, we define the resilience indicator as the average of NCI and ϕ.

3. Results and discussions

To analyze the applicability of the proposed indicator, we create four illustrative cases, where the connections among the participants are different in each of them (Table 1). Finally, to demonstrate the applicability of the proposed indicator to reality, we compose a new case considering all the previous examples, so as to address a new scenario with a higher complexity.

Table 1: Illustrative cases and their values of NCI, ϕ, and resilience indicator.

Example	Configuration	Results	Example	Configuration	Results
1		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.25$ $Resilience = 0.125$	3		$\phi_1 = 0.667$ $\phi_2 = 0.5$ $\phi_3 = 0.125$ $\phi_4 = 1$ $\phi_{config.} = 0.573$ $NCI = 0.25$ $Resilience = 0.441$
2		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.5$ $Resilience = 0.25$	4		$\phi_1 = 0$ $\phi_2 = 0.25$ $\phi_3 = 0$ $\phi_4 = 0.2$ $\phi_{config.} = 0.112$ $NCI = 0.25$ $Resilience = 0.181$
5	(Park)	$Resilience = 0.249$			

The first sub-indicator, NCI, considers the topology of a network, measuring the existence of connections in the park using the number of connections among the firms. Accordingly, if a network obtains a high NCI value, there are a lot of connections in the park, and therefore, the network does not loose connectivity when a disruptive event occurs. In contrast, if a network obtains a low NCI value, the park is weakly connected, and thus, the network has isolated participant during disruptions. This behavior can be seen on examples 1 and 2 (Table 1), where as the number of connection grows, the NCI increases its value. In the first example, if one participant interrupts its activity, it is highly probable that the network has isolated nodes. For instance, if the participant 2 interrupts its activity, participant 1 will loose connectivity. Conversely, in the example 2, since all participant have two connections, forming a closed loop, they will be always connected if any of them suffers a disruptive event. For example, if participant 2 interrupts its activity, the network maintains its connectivity. For this reason, the last configuration has the highest NCI value.

The second sub-indicator, ϕ, considers the performance of an industrial network, measuring the magnitude of the sharing flows and the feasibility of their substitution during disruptions. Therefore, if a network obtains a high ϕ value, the participants can endure the activity interruption of any of them, and therefore, the network can continue working.

We can observe on example 1, 3, and 4 (Table 1) the performance of this indicator, where the number of connections is kept constant ($NCI = 0.25$ for both of them), but the connected participant are changed. In the example 1, since all the participants obtain $\phi_k = 0$, they cannot be replaced, and therefore, the network cannot endure any disruptive event. In the example 4, the connection between participant 2 and 4 is changed for the connection between 1 and 4. This change makes modify the ϕ value of the network, suffering a little increase compared to the previous example. In this new configuration, participant 2 and 4 can be partially replaced for the other members when they suffer a disruptive event. In the example 3, the connection between participant 1 and 4 of the example 4 is changed for the connection between 1 and 3. In this new configuration, all the participant can be partially replaced by the other members, then ϕ of the network grows. This is because as some participants have more than one inputs or outputs, they do not depend just on one of them.

On the other hand, it is worth to note that the Flow adaptability index depends on the capacity of each firm to change the magnitude of its inputs and outputs, and on the connectivity of the participants. In consequence, ϕ depends on NCI.

An eco-industrial park is composed by a set of firms sharing different type of materials (e.g. water, biomass, oil, etc.). Each of these exchanges can be analysed through different sharing layers belonging to the same park, or by unconnected subsets within the park. In this context, two known examples in the literature are Kalundborg (Knight (1990)) and Ulsan (Behera et al. (2012)). In the first case, the industrial network is composed by different sharing layers, where the same set of firms share water, sludge, steam, among others; in the latter, there are different unconnected subsets of firms sharing different type of materials, as steam, waste oil, and zinc powder, among others. An illustrative example is provided with this logic. It considers a park composed by all the previous examples, sharing different type of material at once. We can estimate the resilience value in this context as the average of the individual resilience values of each sub-network (Table 1).

A better estimation of the resilience value of the whole park is proposed for further works, because the integration of multiple sharing layers or subsets can evolve from an average to another function, so as to improve the assessment of real industrial parks.

4. Conclusions

We propose an indicator to measure the resilience of an EIP and to support future application in optimization problems in the design phase of eco-industrial parks. This indicator is based on two characteristics of an industrial network: its topology and its operation. These aspects are measured by two sub-indicators: NCI and ϕ, respectively. The first one measures the number of connections in order to maintain the connectivity of the participants during a disruption event. The second sub-indicator measures the capacity of the participants to modify their flows and to replace the loosed ones when a disruptive event occurs. Both sub-indicators are integrated, composing a global resilience indicator.

The resilience indicator has been applied over five examples, where the number of connections and the orientation of them are modified. We obtain consistent results regarding both sub-indicators and the resilience indicator. It is important to remark the need to construct a good estimation of the resilience of a whole park, where different type of material is exchanged among the participants. Besides the number of connections conditions the resilience, their orientation has significant effects on the resilience indicator. It is important to remark that there is a dependence between ϕ and NCI, since the existence of a flow requires the existence of connections. In consequence, further work can be done to integrate ϕ and NCI so as to compose a resilience indicator.

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