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Understanding resilience in industrial symbiosis networks: Insights from network analysis

Shauhrat S. Chopra, Vikas Khanna*

Department of Civil and Environmental Engineering, University of Pittsburgh, 742 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261, United States

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ABSTRACT

Industrial symbiotic networks are based on the principles of ecological systems where waste equals food, to develop synergistic networks. For example, industrial symbiosis (IS) at Kalundborg, Denmark, creates an exchange network of waste, water, and energy among companies based on contractual dependency. Since most of the industrial symbiotic networks are based on ad-hoc opportunities rather than strategic planning, gaining insight into disruptive scenarios is pivotal for understanding the balance of resilience and sustainability and developing heuristics for designing resilient IS networks. The present work focuses on understanding resilience as an emergent property of an IS network via a network-based approach with application to the Kalundborg Industrial Symbiosis (KIS). Results from network metrics and simulated disruptive scenarios reveal Asnaes power plant as the most critical node in the system. We also observe a decrease in the vulnerability of nodes and reduction in single points of failure in the system, suggesting an increase in the overall resilience of the KIS system from 1960 to 2010. Based on our findings, we recommend design strategies, such as increasing diversity, redundancy, and multi-functionality to ensure flexibility and plasticity, to develop resilient and sustainable industrial symbiotic networks.

1. Introduction

Industrial Symbiosis (IS)- a mutually beneficial relationship between industries that achieves productive use of waste and by-products- promotes sustainable development by providing economic benefits while minimizing environmental degradation caused by the participating industries. IS was investigated with much curiosity from the 1925–1960's in the field of Economic Geography (Appleton, 1929; Frey, 1929; Morrison, 1944; Zierer, 1941) to understand geographically localized synergies of by-products, however it fell out of the radar until appreciation for its ability to mitigate environmental impacts rekindled a renewed interest many decades later (Desrochers and Leppälä, 2010). Growing interest in the field of IS and attempts to develop theoretical approaches to understand the resilience of IS networks is being pursued with equal vigor in both developing and developed countries of the world. *The Roadmap for a Resource Efficient Europe* supports and encourages all European Union (EU) member countries to employ IS for maximizing resource efficiency (EC, 2011; Lombardi et al., 2012). Similarly, Organization for Economic Cooperation and Development (OECD) recognizes IS as a tool for fostering green growth and eco-innovation and recommends its application (Laybourn and Lombardi, 2012; Zhou et al., 2012). Moreover, developing economies from Asia such as China and India have been extensively exploring and experimenting with Eco-Industrial Parks (EIP's) (Bain et al., 2010; Ferrer et al., 2012; Shi et al., 2012).

While IS networks are highly complex and resource efficient with substantial economic and environmental benefits to the participating industries, they can also be vulnerable to unanticipated perturbations. A disturbance affecting even one industry (or node in the system) may lead to a domino effect, resulting in cascading impacts on the rest of the network (Allenby and Fink, 2005; Boons and Spekkink, 2012). Additionally, since most synergies in an IS network may be a result of social interactions between managers and owners of industries, the resulting network may not be strategically planned and be coincidental in nature, which makes it vulnerable to unforeseen and catastrophic events (Bain et al., 2010; Chertow, 2000, 2007; Ehrenfeld and Gertler, 1997). The need for understanding the theoretical framework of IS for guiding their resilient design has been identified, but has only received limited attention (Ruth and Davidsdottir, 2009a, b). Resilience has drawn attention in studies aimed at advancing risk adaptation in supply chain management (Christopher and Peck,

* Corresponding author. Tel.: +1 412 6249603.
E-mail addresses: shc82@pitt.edu (S.S. Chopra), khannav@pitt.edu (V. Khanna).

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2004; Pettit et al., 2010) and to ascertain mechanisms promoting resiliency in ecological networks (Folke, 2006; Gunderson, 2000; Holling, 1996; Walker et al., 2004). Zhu and Ruth compare and contrast the concept of resilience in ecological systems and supply chains to inform its application for IS systems (Zhu and Ruth, 2013). Borrowing the understanding of ecological resilience, we define resilience as the capability of a system to absorb disruptions while maintaining its structure and function (Allenby and Fink, 2005; Fiksel, 2003, 2006; Korhonen and Seager, 2008). This property allows an IS network to absorb known or unknown stresses that would otherwise disintegrate the system and leave the participating industries dysfunctional.

Past research on IS has focused primarily on genesis and evolution of IS networks (Ashton, 2009; Chertow, 2000; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Lombardi et al., 2012; Paquin and Howard-Grenville, 2012), defining the IS system and its boundaries (Chertow, 2000) and the impacts of implementing IS networks (Chen et al., 2012; Chertow and Lombardi, 2005; Cimren et al., 2011; Kovács, 2012). Most of these studies adopt a biophysical approach to quantify resource savings and emissions reductions in IS systems by applying the concepts of industrial ecology (Chertow, 2000; Ehrenfeld and Gertler, 1997; Jacobsen, 2006). Amongst biophysical approaches, life cycle assessment (LCA) is frequently being used as a decision making tool to estimate and compare the environmental impacts of various synergetic exchanges in an IS context. (Grießhammer et al., 2006; Mattila et al., 2012, 2010; Nelson, 2007; Pelletier and Tyedmers, 2011; Sokka et al., 2011). There have also been attempts to recognize the importance of social factors for coordination and organization of actors for initiating synergies (Bain et al., 2010; Boons and Spekkink, 2012; Ferrer et al., 2012). Social Network Analysis is one such technique applied on Kalundborg IS to understand its organizational framework (Domenech and Davies, 2011). Furthermore, research on the design of IS for specific regions and industry types, for instance modeling coal-chemical IS in China, has provided a viable option to mitigate emissions and achieve high value-added utilization of resources (Zhou et al., 2012). However, except for Zhu and Ruth's recent work on robustness of IS networks to removal of industries from the network, none of the other studies have focused on studying the resilience of highly interconnected and symbiotic industrial network in a rigorous quantitative manner (Zhu and Ruth, 2013). There still exists a void in the resilience assessment of IS systems, since most of the synergies are "strictly business" and ad-hoc in nature that may render the system fragile and highly vulnerable to perturbations (Jacobsen, 2006; Lombardi et al., 2012).

IS systems demonstrate self-organizing capability, similar to complex adaptive systems like natural ecosystems, to maintain their functionality to counter stresses (Ashton, 2009). Understanding resilience of such complex networks will aid in assessing the capacity of the system to retain its function by maintaining its structure while under stress (Fiksel, 2006). However, there is a notable disparity in the understanding of resilience in the context of engineered systems. It has been argued that a close relationship exists between resilience and sustainability where the former concept is a prerequisite for the latter (Common and Perrings, 1992; Fiksel, 2006; Lebel et al., 2002). On the other hand, some researchers consider resilience equivalent to sustainability (Common and Perrings, 1992; Levin, 1998; Walker et al., 2004) and while a few others consider resilience inadequate for attaining sustainability in specific instances (Derissen et al., 2011; Walker et al., 2004). However, among all the uncertainty surrounding the relationship between resilience and sustainability, the need for developing resilient and efficient IS networks for improving sustainability, is a certainty.

Most existing methods for sustainability assessment including those based on life cycle thinking employ biophysical approaches to quantify the resource flows and environmental impact of products and processes. However, these methods assume a simple cause–effect relationship and may ignore the indirect effects due to the system-wide interactions between the network components (Ruth and Davidsdottir, 2009a, b). On the other hand, network analysis employs methods and metrics such as centrality or connectivity indices to understand the network structure and the underlying complex set of relationships among the nodes (Zhu and Ruth, 2013). However, network analysis has not been applied extensively to enhance understanding of resilience in engineered networks. We attempt to bridge this gap by integrating the concepts of network theory with information about resource flows to understand resilience and vulnerabilities in industrial symbiotic networks. We focus our attention on the Kalundborg Industrial Symbiosis (KIS) located in Kalundborg, Denmark due to availability of public information for this Eco-Industrial Park. We extensively use the 2002 snapshot of the water synergy network at KIS, due to availability of data for this period, to reveal industries with the highest vulnerabilities, using network metrics like centrality indices and network efficiency, and suggest strategies for designing resilient future IS systems. In addition, we explore the evolution of the Kalundborg industrial symbiosis network and analyze time trends in node-level metrics and connectivity indices for gaining an understanding of the resilience. Our present work aims to deliberate on a network-based approach for understanding resilience in IS networks and plugging the gaps in foundational framework for IS.

The rest of the article is organized as follows. Section 2 provides a detailed description of the IS at Kalundborg. It also describes the metrics and the methods used to assess vulnerabilities in the system through disruptive scenarios, the evolution of resilience over time, and calculation of hypothetical economic and ecological savings resulting from synergistic exchanges. Section 3 presents the results of the study. A discussion of the results and strategies for the design of resilient IS system is in Section 4. Lastly, a summary of the main findings is provided in Section 5.

2. Material and methods

2.1. System description

IS at Kalundborg, Denmark consists of a synergistic network of waste and by-product streams among companies based on contractual dependency (Chertow, 2007; Ehrenfeld and Gertler, 1997). KIS originated in the early 1960s as a strategy to reduce exploitation of groundwater in the region in the face of a growing groundwater deficit and an increasing water demand by the industries (Ehrenfeld and Chertow, 2002). Subsequently, it has developed from a water exchange network to a network with more than 30 different by-product synergies (Jacobsen, 2006; KS, 2013). The synergistic flow of by-product and waste streams between the power plant, the oil refinery, the district municipality, and other industries in the region of Kalundborg has not only led to an increase in the resource efficiency but also to the economic gains of the participating industries (Chertow, 2007; Chertow and Lombardi, 2005; Jacobsen, 2006).

As shown in Fig 1, IS at Kalundborg includes disparate industries such as the Asnaes power plant, the Statoil refinery, the Novo Group- a pharmaceutical company, as well as the local municipality that exchange by-product and resources amongst themselves. Since not all participating industries require the same quality of water, the water synergy network includes raw water from surface water and groundwater, as well as used industrial water in the form of