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Improving Cleaner Production through Biologically Inspired Urban-Industrial Networks

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Abstract

Biologically-Inspired Design is a growing field that has many applications. While this is normally used for individual products or materials, applied at a systems level, the inspiration stems from the structure and makeup of ecosystems. Over the last few decades, ecologists have developed Ecological Network Analysis (ENA) to better understand ecosystems, and both industrial and urban systems have been analyzed using ENA. Specifically, Eco-Industrial Parks (EIPs) that look to mimic the cyclic nature of food webs have been analyzed using ENA showing that these networks can still be improved significantly before they reach the levels of observed natural food webs. Similarly, urban networks (such as water and energy networks) have been looked at with ENA at a high level with insight gained about trophic levels in a city and how they compare with food webs. However, the industrial and urban networks have been analyzed at different scales and in separate systems. In this paper, we propose to further the use of ENA for industrial and urban networks. Specifically, the industrial networks will be combined and analyzed with the urban networks. This better represents how these networks function in reality whereas before some critical connections may have been ignored. A case study will be used to exemplify the method and benefits of our approach.

Keywords: *biologically-inspired design, ecological network analysis, industrial ecology*

1. Motivation

1.1 Industry

The industrial sector is extremely resource intensive. Industrial energy consumption is 22% of total energy consumption in the United States (US Energy Information Administration 2017), with irrigation, livestock, aquaculture, industrial and mining processes accounting for 42% of all water withdrawals (US Geological Survey 2010). In addition, raw material usage in the U.S. rose almost 3 times faster than population from 1910 to 2010 (Center for Sustainable Systems 2016). As such, there have been a number of efforts to curb industrial resource usage. The US Environmental Protection Agency created a program called E3 focusing on increasing sustainability of communities, manufacturers, and supply chains (US Environmental Protection Agency 2017). Many specific industries have also made this a goal such as automotive plants using landfill gas to power onsite energy and heat generation (BMW 2014). Beyond the individual industry level, there has also been a lot of work on industrial networks to move towards sustainability. This has led to the concepts such as Industrial Ecology (Frosch 1992) and industrial symbiosis (Earley 2015) where the goal is to understand these networks in a similar way to ecological systems and create symbiotic relationships between industries. Industrial ecology and cleaner production have similar goals, and the adoption of cleaner production practices can lead to achieving the overall sustainable development goals of Industrial Ecology (Berkel et al. 1997; Basu &

van Zyl 2006). Furthering the concept of Industrial Ecology into practice led to the creation of Eco-Industrial Parks (EIPs) that looked to mimic the connectedness of natural ecosystems (Hardy & Graedel 2002).

1.2 Cities

Similar to industry, cities are a critical component of today's society. Currently, half of the world's population lives in cities, and this is expected to grow to 60% by the year 2030 (United Nations Habitat 2015). With this large concentration of population, cities are also very resource intensive. While only taking up 3% of the land area of the globe, cities consume 60-80% of the energy and produce 75% of the carbon emissions (United Nations Habitat 2015). In addition, the 27 megacities, defined as having a population of 10 million or more, consume 9% of all electricity, 10% of all gasoline, and generate 13% of all solid waste (Kennedy et al. 2015). This growth and resource usage puts a large stress on water supplies, the living environment, and human health. The United Nations has made it one of their sustainable development goals to "make cities inclusive, safe, resilient and sustainable," with other goals pertaining to clean water, clean energy, and combating climate change (United Nations 2015). Urban infrastructure plays a critical role in cities, as it is what allows the city to function. This infrastructure is becoming increasingly vulnerable as climate changes and as populations grow. There is an obvious need to tackle the issue of growing cities, especially in regards to the infrastructure that supports them.

Kenworthy has proposed principles of an "eco-city" that revolve around urban form and transport (Kenworthy 2006). Dias et al suggests that there is a need to rethink urban design as a bottom up approach to create more sustainable cities (Dias et al. 2014). Others have proposed green urbanism (Anastasiadis & Metaxas 2013), green infrastructure (Tzoulas et al. 2007; Ahern 2007), and landscape ecology (Wu 2008), all of which look to better integrate the human and built environment with the living one.

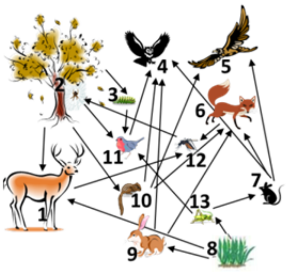
Cities in the US were typically built around the industries located there, but most of this industry has been pushed to the hinterlands in favor of services. However, industry is still very much tied to the sustainability of cities. There is enormous potential to make industry more efficient, benefitting both industry and the cities it is located within (Sall & Shah 2015). It has been recommended to increase the amount of industrial mixed-use districts and light industry within cities to increase economic and social viability (Cotter 2012). Efforts to increase city sustainability have seldom focused on industry, instead focusing on infrastructure and planning. However, there is potential to adapt the ideas of industrial ecology to cities. Urban networks, like industrial ones, consume the same resources and can be modeled in the same way. This paper looks to apply the concepts of industrial ecology to cities in order to achieve cleaner production.

2. Background

2.1 Ecological network analysis

As one would imagine, the main inspiration of Industrial Ecology comes from natural ecology. Natural ecological systems (ecosystems) have been analyzed for many years using Ecological Network Analysis (ENA). This analysis revolves around the interactions of organisms within the network primarily focused on what is consuming what and what is the rate of consumption (Ulanowicz 2004). This analysis takes food webs and represents them as a network of connections between the different organisms present. The organisms (or aggregation or organisms) are often referred to as actors. The connections between the actors represent energy exchanges which can be measured in different ways but is often represented as grams of carbon per square meter per year (Allesina et al. 2005).

Ecological literature defines metrics that examine ecosystem properties and species interactions (see, e.g., (Briand & Cohen 1987; Schoener 1989; Odum 1969; Pimm 1982; Warren 1990; Cohen et al. 1993; Ulanowicz 1999)). The flows of materials and energy in an ecosystem and its food web can be represented in a food web matrix [**F**]. The interactions are organized between predators (columns, resources flow to predators) and prey (rows, resources flow from prey). Figure 1 shows a hypothetical food web represented as a directional digraph (left) and converted into a food web matrix (right). Since a species (*N*) can be both predator and prey the result is a square matrix. A value of 1 indicates the existence of a directional flow from row to column and a zero indicates no connection. In other words, if predator-*j* feeds on prey-*i*, then $f_{ij} = 1$; the interaction (or link, *L*) is accounted for exactly once in the food web matrix. The maximum number of links, *L* scales as $(N)*(N-1)$ if cannibalism is not allowed and N^2 if it is (noted as a 1 on the diagonal).



$$\mathbf{F} = \text{prey}\ \overset{\text{predators}}{\begin{array}{r|ccccccccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
7 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\
9 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
11 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
12 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
13 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0
\end{array}}$$

Fig. 1. Left – A food web of a hypothetical ecosystem with species numbered. Right – A food web matrix; $f_{ij} = 1$ represents a unidirectional link between prey (*i*) and predator (*j*) and a zero represents no link.

A wide variety of metrics have been developed to understand the link between structure and behavior of ecological systems (Fath & Halnes 2007; Bascompte & Jordano 2007). The structural measures and metrics used most frequently by ecologists can be calculated using the *N* x *N* structural food web matrix shown in Figure 1. These metrics can be calculated knowing only structural information, that is, all calculations per equations 3 to 14 are simply based on binary information on whether a link exists between two actors in the matrix, or not. f_{ij} represents the linkage between actor *i* to actor *j* and is the i^{th} row and j^{th} column entry in the matrix with a value of either 1 (link exists) or 0 (no link). Linkage density (L_D) is the number of links in the system normalized by the number of actors in the system (Dunne et al. 2002). The number of prey and predators (n_{prey} and $n_{predator}$) are the number of actors that provide and consume a resource respectively (Schoener 1989), or producers and consumers in industry terms, respectively. The ratio of these two is the prey to predator ratio (P_R) a numerical representation of the balance of consumers to producers in the system. The number of specialized predators ($n_{S\text{-}predator}$) is a subset of $n_{predator}$ and only counts those consumers who interact with only one actor. The specialized predator ratio (P_S) is the fraction of consumers that are specialized. Generalization and vulnerability (*G* and *V*) are subsets of L_D and represent respectively, the number of producers that a consuming-actor can consume and the number of consumers a producing-actor provides flows to (Schoener 1989; Pimm 1982). Connectance (C) is the number of realized direct interactions in a web divided by the total number of possible interactions. If one forbids cannibalism, then the denominator is the fraction of nonzero off diagonal elements in the foodweb matrix [**F**]. Cyclicity (λ_{max}) is the maximum real eigenvalue of the transpose of the food web structural matrix (flow is columns to rows). Cyclicity represents the presence and complexity of internal cycling in the system (Fath & Halnes 2007; Borrett et al. 2007; Fath 1998; Layton et al. 2012), and is taken as an indication of how cyclic pathways proliferate as the number of steps in the cycle grows. More detailed descriptions of these metrics may be found in (Layton et al. 2016b) in addition to the references already listed.

$$L_D = {}^{L}\!/_{N} \tag{1}$$

$$f_{row}(i) = \begin{cases} 1\, for \displaystyle\sum_{j=1}^{n} f_{ij} > 0 \\ 0\, for \displaystyle\sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{2}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i) \tag{3}$$

$$f_{col}(j) = \begin{cases} 1\, for \sum_{i=1}^{m} f_{ij} > 0 \\ 0\, for \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{4}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{5}$$

$$P_R = {}^{n_{prey}}\!/_{n_{predator}} \tag{6}$$

$$f_{s-col}(j) = \begin{cases} 1\, for \sum_{i=1}^{m} f_{ij} = 1 \\ 0\, for \sum_{i=1}^{m} f_{ij} \neq 1 \end{cases} \tag{7}$$

$$n_{S-predator} = \sum_{j=1}^{n} f_{s-col}(j) \tag{8}$$

$$P_S = {}^{n_{S-predator}}\!/_{n_{predator}} \tag{9}$$

$$G = {}^{L}\!/_{n_{predator}} \tag{10}$$

$$V = {}^{L}\!/_{n_{prey}} \tag{11}$$

$$C = {}^{L}\!/_{N}2 \tag{12}$$

$$\lambda_{max} = max, real\ eigenvalue\ solution\ to: 0 = \det(\boldsymbol{A} - \lambda \boldsymbol{I}) \tag{13}$$

2.2 Eco-industrial parks

As stated previously, the concept of Eco-Industrial Parks (EIPs) has come out of Industrial Ecology. EIPs look to mimic natural food web structure and form, and not only that they can be mimicked, but also that there is “an analogous relation between biological and industrial food webs, and tools for evaluating the former are valid for the latter” (Hardy & Graedel 2002). Given the inspiration of the EIPs, ENA would be an appropriate form of analysis for these systems. Through the study and analysis of 48 EIPs using ecological principles metrics, it has been shown that these systems do not perform as well as natural food webs. They lack both the complexity and functional roles of natural ecosystems meaning the EIPs have lower values for cycling and density of connections (Layton et al. 2016b). Given this lack of complexity, Layton et al. attempted to combine EIPs together to increase the complexity of these systems to better mimic natural ecosystems. It was found that simply adding connections is not enough to improve the performance of the EIPs relative to the natural ecosystems, but instead, meaningful connections, such as the inclusion of detritus actors and decomposers (organisms that break down dead organic matter into usable material for plants), must be made to improve performance (Layton et al. 2017). This theoretical incorporation of multiple EIPs together can be seen as a step towards higher performing human systems, but could be expanded further to include more industrial and urban systems. In addition, it has been shown that there is a strong correlation between these ecological metrics and traditional sustainability metrics of cost and air emissions in a carpet recycling network (Layton et al. 2016a).

2.3 Cities and Ecology

In addition to the industrial applications of ecology, cities have often been analyzed in a similar light. One of the best examples of this is urban metabolism. Urban metabolism attempts to draw the parallel between cities and ecological processes by quantifying “the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al. 2007). In this way, urban metabolism is an accounting method for what goes into and out of a city. However, a review of over 100 urban metabolism studies showed there is a large variance in how these studies are done, and there is still room for improvement in this method, with one of the main challenges being "how to model the system's network" and realize "its effects on the environment" (Beloin-Saint-Pierre et al. 2015). Also, urban metabolism has been criticized for modeling cities as organisms rather than ecosystems, which hinders the view of the city as a network and reduces it down to a single entity (Golubiewski 2012). A review of other ecological approaches in planning cities found that there is "a need for developing an accurate and comprehensive micro-level urban ecosystem sustainability assessment method that also have the capability to be integrated with larger scale assessment tools" (Yigitcanlar & Dizdaroglu 2015). There have been some applications of ENA to urban systems (Chen & Chen 2016; Zhang, Yang & Fath 2010; Zhang, Yang, Fath, et al. 2010), but these systems have been at a very high level and do not necessarily provide deep insight into the complex interactions of cities. As shown in Fig. **2**, the urban systems being analyzed with ENA exhibit the same network structure as the food webs described previously.

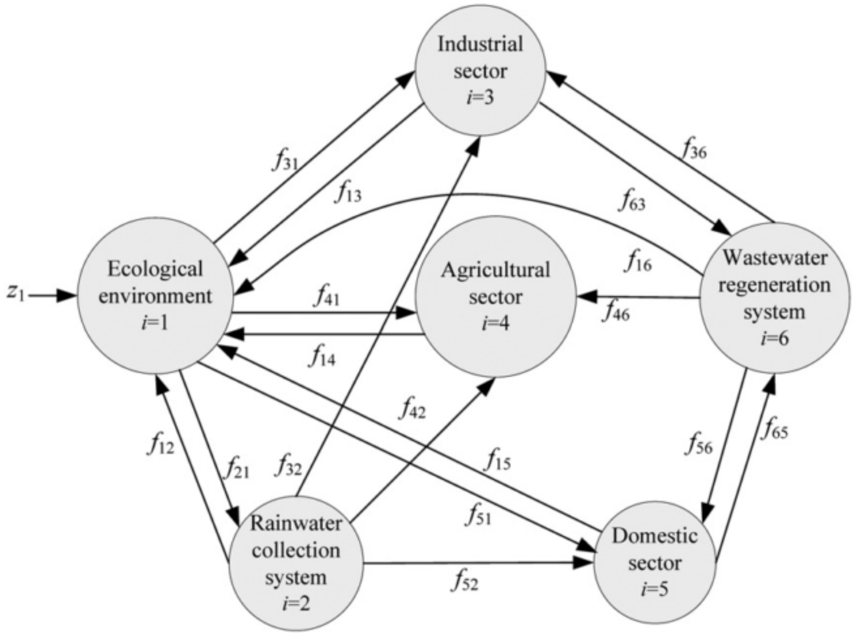


Fig. 2. Ecological network model of urban water metabolic system (Zhang, Yang & Fath 2010)

Xu et al states that "analogies to ecological systems may reveal new ways to analyze urban systems and provide design and decision guidelines for sustainable cities," and thus has proposed the idea of infrastructure ecology to capture and analyze the intricacies of urban infrastructure systems (Xu et al. 2012). With this proposal, they have also offered a number of research questions fundamental to infrastructure ecology. These questions raise issues with how to translate ecology to infrastructure, the scale at which these analogies can be applied, the fundamental structure of urban systems, and new ways to organize infrastructure that can be tested and compared with one another (Xu et al. 2012). Furthermore, 12 major principles of infrastructure ecology have been proposed by Pandit et al (Pandit et al. 2015). These principles center around the integration of systems, synergizing between engineering and ecological systems, and considering socioeconomics and stakeholder preferences in all designs and decision. They provide guidance into how to think about infrastructure design and implementation. However, these principles have not been tested or incorporated beyond the ideation phase, and therefore their impact has yet to be seen.

It is clear there is a desire to incorporate ecology into both industry and cities, but many of these ideas stop short of fully integrating the ideas of ecology. EIPs have looked to directly mimic ecosystem structure, but they do not include the greater surrounding connections that may explain the current inferior complexity when compared to natural ecosystems. Cities have not been viewed with enough detail to ascertain any significant characteristics about the network structure. Combined, however, these two lenses may provide a greater level on insight into how both cities and industry are structured and function.

3 Industrial Case Study

To look at how this analysis can be used, a case study is presented illustrating an urban-industrial network as it currently stands and with modifications made to move toward cleaner production. This case study in particular looks at water as it is one of the major resources shared between cities and industry. A hypothetical water network can be created to show the effect of creating an urban-industrial ecosystem, how it can be modified, and how it is analyzed using ENA. For this example, there will be focus on a single, large manufacturer in a relatively smaller city to better see the effect of the creation of the network. The hypothetical manufacturing plant is connected with the city water supply and sewage network. In the network, the plant and all others in the region are completely dependent of this municipal supply for water. Given this, there is the opportunity to modify this network in order to increase water resiliency for both the city and the plant.

The current network configuration was assumed to be a typical water system where the municipality supplies water to all actors. This configuration is shown in Fig. 3(a). There are a number of modifications that can be made to the baseline network to try and improve the overall performance. The first modification is to add a rainwater capture system to the main manufacturing plant. This allows the plant to offset some of its water demand, thus lowering the stress on the main municipal water supply. In this scenario, additions were made to the existing network to include the capture technology and some way for the manufacturing plant to distribute that water around the plant. The next modification was to add a graywater treatment option for the manufacturing plant. In a similar way, this reduces some of the demand from the municipal water supply by reusing some of the water that is already in the plant. This modification added with the rain capture system can have an even greater impact, in addition to spreading the load of water to even more sources for the plant. The final modification was to assume the plant could capture enough water to distribute excess to the surrounding community. In this configuration, every water consumer in the network now has the choice of two different water supplies, lessening the stress on any single load. This scenario is shown in Fig. 3(b). These scenarios look at the effect that adding cleaner production methods for water has on the network when compared to the current configurations. Using the ENA method, a matrix of connections was created for these different ecosystem configurations. The actors in this ecosystem include the municipal water distribution, the municipal sewage system, the main manufacturing plant, the local suppliers to that plant, the residential area, and agriculture. From Fig. 3, it is clear that more connections are being added, especially in the final configuration, but as stated earlier, more connections does not always lead to better ecological performance (Layton et al. 2017).

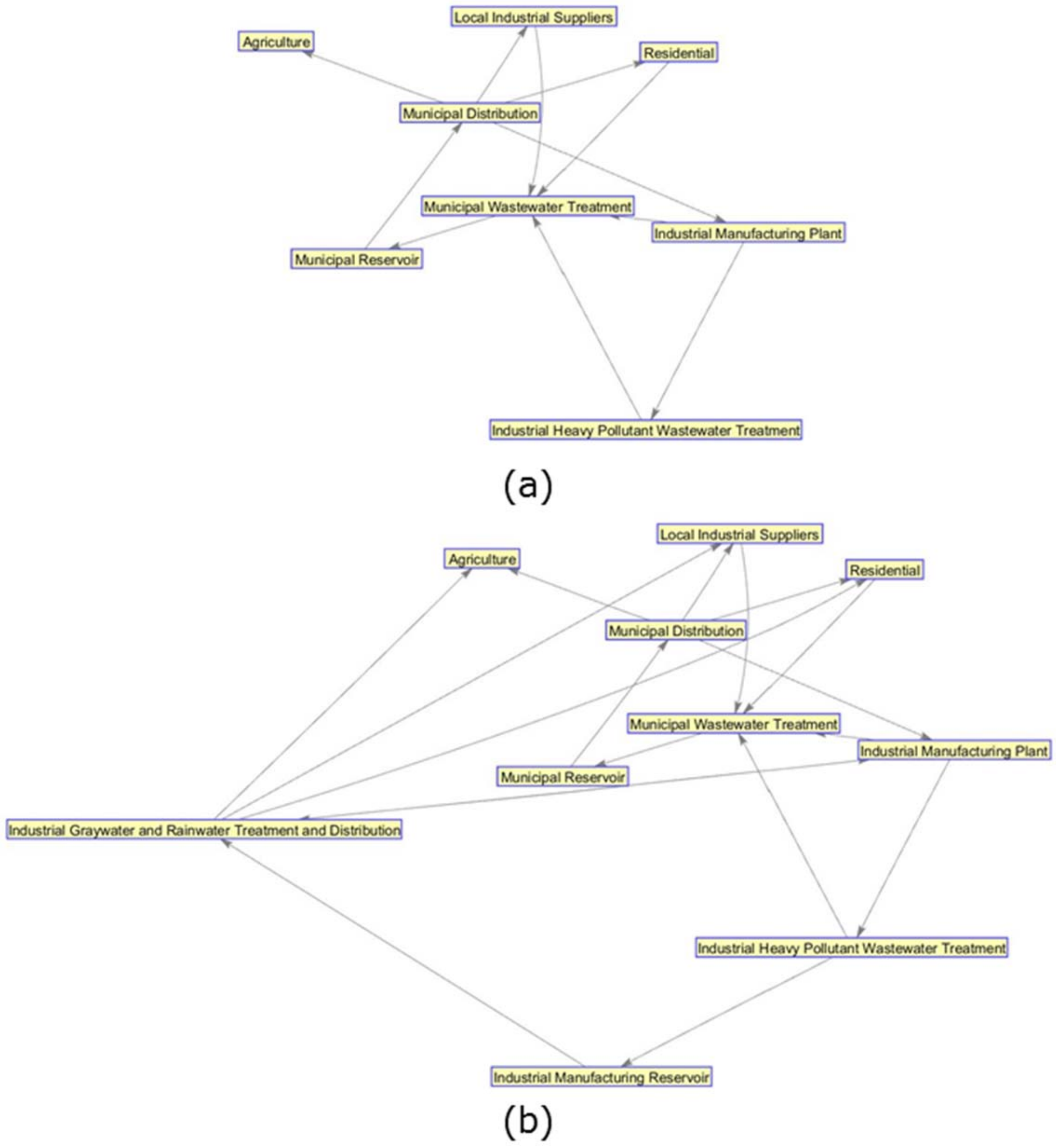


Fig. 3. Configurations of urban-industrial water network with boxes representing actors and arrows representing a flow of water. (a) Current configuration (b) Community oriented expansion of the network

The different network scenarios described above were evaluated using the structural ecological metrics previously described in equations 1 through 13. The resulting values for the different water networks described above are given in Table 1. Each metric describes a different aspect of the network, but one of particular interest is the cyclicity as it looks at the cycling of the network and generally speaking more cycling can lead to a reduction in resource consumption. Looking at the cyclicity value for each configuration, all values are above 1, meaning there is at least one cycle present within the system. This is as expected due to wastewater being treated and put back into the system at the municipal level. There is an increase in the cyclicity for the rainwater capture configuration from the current. There is a further increase in cyclicity for the rainwater capture and graywater configuration. Finally, the community oriented configuration has the largest cyclicity meaning the most cycling is present within this system. The increase of the cycling is beneficial because more of the water is able to be reused before exiting the system. However, these values are still low compared to natural ecosystems. Natural ecosystems can have a cyclicity of up to 14, with the average value being over 4. In addition, existing EIPs that have been analyzed have a maximum cyclicity value of around 2.5 (Layton et al. 2016b). This shows from a cycling perspective, there is still a lot of improvement that can be made.

Table 1. Ecological metrics for urban-industrial water network

	Current configuration	*Rainwater capture*	*Rainwater capture and graywater*	*Community oriented expansions*
Cyclicity	1.39	1.43	1.56	1.64
Linkage Density	1.38	1.40	1.50	1.80
Predator Prey Ratio	0.88	0.90	0.90	0.90
Generalization	1.38	1.40	1.50	1.80
Vulnerability	1.57	1.56	1.67	2.00
Actors	8	10	10	10
Links	11	14	15	18
Number of Predators	8	10	10	10
Number of Prey	7	9	9	9
Connectance	0.17	0.14	0.15	0.18

This analysis only looks at the structure of this network, but the amount of flow is also important to note. In all of the proposed configurations, there is less water demand from the municipal supply by the industrial manufacturing plant and therefore less demand on the source of the municipal supply. If this is a water scarce region or a dwindling source, this could have a very positive effect on the water network by reducing stress on a scarce resource. The new source, assuming it is coming from a rain capture system, puts no added stress on the system because the supply is rain water that would otherwise be lost anyway. Therefore there is a more sustainable source of the water leading to cleaner production overall. However, there is new infrastructure that must be put in place to process that water. This new infrastructure and processing has the potential to reduce overall energy consumption by reducing the amount of water transported to the manufacturing plant, but this would depend on the exact network. Regardless of that infrastructure, it is clear that the new configurations reduce stress on the existing water supply.

4. Conclusion and future work

The need for cleaner production in industry is clear, but this need is very easily translated over to urban systems and environments as well. The reality is that industry does not exist in a vacuum, and as such it cannot be treated or analyzed within a confined industrial network. These industrial networks can and should be expanded to reach urban networks as they are critical to the overall goals and process of cleaner production. Industrial Ecology provides a great framework with which to expand the analysis of industrial systems to combined urban-industrial networks. Specifically, ENA can be used in these networks to provide greater insight into the network structure and sustainable performance. Shown here is how the ENA method can be applied to an urban-industrial network, and how the performance of different configurations can be compared. The case study here is a simple one, but ENA can be used for much larger networks with much greater complexity.

Furthering this work will include constructing and analyzing more networks with ENA. The proposed method has been used in a few very specific ways thus far, but the use is still in its infancy. There are only a handful of industrial and urban networks that have been analyzed in this way, but the possibilities of the analysis extend beyond that to any network. Using ENA on more networks will prove the usefulness of this as both an analysis and design tool. Understanding gained from the analysis of many networks can lead to design principles that can be applied to future urban-industrial networks. In addition, further testing needs to be done to prove the conclusions of Layton et al. that an improvement in ecological metrics correlates with an improvement in traditional sustainability metrics (Layton et al. 2016a).

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