# FOOD WEBS: REALIZING BIOLOGICAL INSPIRATION FOR SUSTAINABLE INDUSTRIAL RESOURCE NETWORKS

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# FOOD WEBS: REALIZING BIOLOGICAL INSPIRATION FOR SUSTAINABLE INDUSTRIAL RESOURCE NETWORKS

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In loving memory of my grandfathers, Joseph Layton and Coen Beunder.

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# LIST OF SYMBOLS, ABBREVIATIONS, AND NOMECLATURE

| | |
|---|---|
| IE | Industrial Ecology |
| EBDM | Environmentally Benign Design and Manufacturing |
| BID | Biologically Inspired Design |
| LCA | Life Cycle Assessment |
| Symbioses | Waste and bi-product exchange networks |
| EIP | Eco-Industrial Park |
| IBS | Integrated Bio-System |
| RRP | Resource Recovery Park |
| BE | Biological Ecosystem (interchangeable with Ecological Network) |
| FW | Food web |
| ENA | Ecosystem Network Analysis |
| Detritus | Decomposing plant and animal parts and or fecal organic matter |
| Detritivores | Consume detritus and play the role of biological decomposers |
| DOM | Dead organic matter |
| $[\mathbf{F}]$ | Food web matrix |
| $[\mathbf{C}]$ | Community matrix |
| $[\mathbf{A}]$ | Adjacency matrix |
| Digraph | Directed graph |
| $S$ or $N$ | Number of Species or Actors (interchangeable with Species Richness) |
| $L$ | Number of Links |
| $L_d$ | Linkage density |
| $n_{prey}$ | Number of Prey |
| $n_{predator}$ | Number of Predators |

| | |
|---|---|
| $P_R$ | Prey to Predator ratio |
| $n_{S\text{-}predator}$ | Number of Specialized Predators |
| $P_S$ | Specialized Predator Fraction |
| $c$ | Connectance |
| $G$ | Generalization |
| $V$ | Vulnerability |
| $\lambda_{\max}$ | Cyclicity |
| $[\mathbf{T}]$ | Flow matrix |
| $CI$ | (Finn) Cycling Index |
| $MPL$ | Mean path length |
| $AMI$ | Average Mutual Information |
| $ASC$ | Ascendency |
| $DC$ | Development Capacity |
| TSO | Total System Overhead |
| $R$ | Robustness |
| $TST$ | Total System Throughflow |
| $TSTp$ | Total System Throughput |

# SUMMARY

This thesis considers the problem of how to design an industrial network to reduce cost, increase efficiency, and reduce environmental burdens. A recent approach is further developed that uses analogies with biological food webs to guide industry design. Studying ecological food webs shows that among the metrics in use, critical quantities of interest for industry design include the internal cycling of energy, the ratio of producers to consumers, and the ratio of efficiency to redundancy in the network. Species and links are the building blocks used to define metrics summarizing these quantities. Ecologically correct analogous definitions of species and links are crucial to the use of this approach. Metrics that are calculated using flow based information are also introduced for use in industry, a significant step forward for bio-inspired network design. A comprehensive data set of proposed, operational, and failed eco-industrial parks is compiled for use with structural food web analyses. A data set of biological food webs is also assembled to calculate sustainable benchmark values used as goals for the industrial designs. An essential difficulty with any bio-inspired design approach is the prevalence of philosophical rather than quantitative analyses. This research quantitatively analyzes components of food web design by reconstructing found relationships from science and engineering 1st principles, specifically using thermodynamic 1st law efficiency. Results from this work have the potential to provide industry-wide cost savings, increase efficiency, and reduce environmental burdens through a reduction in raw material consumption and waste disposal. The results also support the view that financial competitiveness and sustainability need not be mutually exclusive: using food web network patterns embodying both economically and environmentally desirable properties, biologically redesigned industrial networks can ease both environmental and economic burdens.

# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation: Industrial Networks and Ecology

The earth currently sustains a population of seven billion people and in 2050 our planet may be home to ten billion. Supporting this growing population, while at the same time providing a viable and sustainable environment, is a dual challenge that can only be met through increased production, more efficient and sustainable industrial processes, and the complete reuse of byproducts. A sustainable global community, one that "meets the needs of the current generation without sacrificing those of future generations (Brundtland 1987) " requires the successful integration of environment and engineering. Success will take the form of a human engineered world which functions more like the one that it is embedded in and on which it depends.

The potential for transferring ecological principles to human systems was recognized decades ago as a way to increase the efficient use of energy and resources and reduce waste (Odum 1969). Designers are quite familiar with nature's repertoire of intelligent designs and strategies. Mammals, reptiles, insects and other organisms are inspiration for well-known bio-inspired products, such as in robotics research for manipulators, grasping devices and locomotion (Waldron 2000). The deflection of bird wings inspired the Wright Flyer's control system (Vogel 1998). The irksome bur inspired the now indispensable Velcro™ (2014).

Biological inspiration has come from 3.85 billion years of evolution (Gamlin and Vines 1987). Over this time ecosystems have developed into cyclical systems where 'waste' and 'resources' are one and the same (Jelinski, Graedel et al. 1992). Making use of ecosystem properties, engineers and designers are working towards biologically preferred closed-loop network configurations that are also desirable from a traditional perspective (Reap 2009, Layton, Reap et al. 2012). In the public and private sectors, designing these cyclical (“closed-loop”) resource networks increasingly appears as a strategy employed to improve resource efficiency and reduce environmental impacts (Ehrenfeld and Gertler 1997, EU 2003).

This is the motivation for the establishment and study of industrial ecosystems, which aims to mimic tried and proven biological ecosystems in industry and manufacturing. Ecological food webs and collections of interacting industries both represent collections of entities (species and industries respectively) that exchange materials and energy (Frosch and Gallopoulos 1989). Industrial Ecology hypothesizes that networks of industries that are designed and/or modified to be analogous to the structure and properties of food webs may approach a similarly sustainable and efficient state (Frosch 1992, Graedel and Allenby 1995, Erkman 1997). Industries that share and/or exchange inputs and outputs, for example raw materials, products, process wastes, or water, are classified together as an industrial ecosystem. When these industries are co-located, then such an industrial ecosystem is also referred to as an eco-industrial park (EIP) (Chertow 2000). A commonly cited example of an industrial ecosystem is the EIP in Kalundborg, Denmark. Concerns over limited ground water supplies in 1961 initiated water reuse between the major companies in Kalundborg, creating mutually beneficial relationships (Hardy 2001, Mitchell 2003, Jacobson 2006). Since then, mutually beneficial relationships have continued to form creating an ecosystem-like structure resulting in reductions on all fronts (Drake 1990, Jacobson 2006, Layton, Reap et al. 2012).

Thus far ecology has acted as more a metaphor than a source for sound EIP design principles (Erkman 2003, Isenmann 2003, Hess 2010, Jensen, Basson et al. 2011); there have been few attempts to translate core ecological principles into industrial practice (but cf. (Garmestani, Allen et al. 2006, Reap 2009)) or validate the analogy between the two systems (Erkman 2003, Layton, Reap et al. 2012). Fath has pointed out that the development of sustainability indicators for ecological and socio-economic systems is of high priority (Fath 2014). Attempts to organize human systems into more ecologically-realistic patterns continue to be based on the “waste equals food” concept (but cf. (Hardy and Graedel 2002)) where the output of a given system component (e.g. industry) provides the input for another. While better than linear models, this type of organization does not accurately reproduce the connecting patterns of ecosystems, preventing the full realization of the analogy. Although many high level comparisons between the two systems have been made, very few quantitative comparisons exist (Reap 2009, Layton, Reap et al. 2012). How the functions of both systems are dictated by their structure (e.g. the topology or input-out connections), and how applied ecological principles change EIP functions needs investigation.

A rigorous and comprehensive analysis can be built by quantitatively comparing a number of characteristically different EIPs to ecological systems coupled with health and function assessment metrics from ecology. Multiple ecosystem structural and material flow metrics that one might use to aid in network design exist (Patten 1978, Ulanowicz 1986, Ulanowicz and Norden 1990, Graedel and Allenby 1995, Fath and Halnes 2007). These metrics quantify commonsense imperatives to reduce and reuse, but they contain limited, if any, information about sustainable thresholds. Identifying thresholds can highlight similarities and differences in the organization of EIPs and food webs, advancing the design of sustainable cyclical industry relationships. Comparing the structure of EIPs and food webs using these ecological parameters can provide guidance for the development of EIPs.

Some metrics however hold the potential to mislead (Naish 2008), and the ecological foundation must be well understood to avoid confusion. Currently there is a mismatch between industry definitions for key ecological terms and industrial application of these terms. To the extent that analogies between natural and human systems are used in an explanatory or predictive manner, key ecological phenomenon must be accurately transcribed to similar processes and phenomenon in industrial systems. This requires an understanding of the ecological process and how components of the process are measured and described.

The extent to which principles derived from ecological systems may be applied in other contexts is unclear. If we can connect the structural properties of ecological networks to well understood physical principles, such as the Laws of Thermodynamics, we might gain sufficient insight to apply ecological lessons to the engineering and development of resource networks.

A robust collection of EIPs is needed for a comprehensive study, particularly as current literature focuses on the Kalundborg EIP (McManus and Gibbs 2008). The small collections of EIPs that do exist also commonly have a high percentage of hypothetical systems. This paper examines the structure of material and energy flows in 48 EIPs (listed in Appendices D and E); more than twice the size and far more detailed than what has been analyzed previously (Brown, Gross et al. 1997, Bennett, Heitkamp et al. 1998, Morton, Simon et al. 1998, Chertow 1999, Johnson, Stewart et al. 1999, Kellogg, Pfeister et al. 1999, Chertow 2000, Hardy, Hedges et al. 2000, Lowe 2001, Chertow, Portlock et al. 2002, Hardy and Graedel 2002, Rotkin, Lubeck et al. 2004, Korhonen and Snäkin 2005, Reap 2009). This dataset contains complete structural information such that food web metrics can be applied and the results compared to food webs. Previous EIP-food web studies used small numbers of food webs (Hardy and Graedel 2002, Fath and Halnes 2007, Reap 2009, Kharrazi, Rovenskaya et al. 2013). The FW dataset used here (listed in Appendix B) has been expanded and updated, and provides new insight into the structural similarities and differences between eco-industrial parks and ecological food webs.

## 1.2 Research Questions and Goals

The overarching objective of this dissertation is to answer the following research question and meet the following research goal:

**Research Question**: Is biological inspiration, in the form of ecological network patterns, principles and metrics, a quantifiably preeminent route for optimizing industrial resource network designs?

**Research Goal:** To understand the behavior of natural ecosystems through their structure and the analyses thereof, such that this knowledge can be applied to the design of sustainable industrial networks, providing new insight on their ecological analysis.

### 1.2.1 Secondary Research Questions and Goals

The overarching research question and goal are broad and can each be reached through a number of smaller research questions and goals.

#### 1.2.1.1 Secondary Research Question 1 (*SubRQ1*)

What is preventing eco-industrial parks from successfully imitating food web structure and function? How can industrial ecology further progress toward its ecological design goal of reaching the sustainable and efficient state characteristic of food webs?

To answer these questions the major limiting factors to progress must be addressed. Misunderstandings of ecosystems and missing ecosystem components are a hindrance to forward progress towards the overarching goal of this work and the field of industrial ecology. The lack of an expansive and complete dataset of EIPs prevents food web-based design decisions from being tested. A current and expansive dataset of food webs is not in use in industrial ecology, resulting in FW goal values that inaccurately reflect food web behavior. The following research goals are proposed to address these concerns:

- **Research Goal 1a)** (*SubRG1a*) Identify fundamental misunderstandings within industrial ecology and fundamental components of a food web missing in eco-industrial parks.

- **Research Goal 1b)** (*SubRG1b*) Provide a useful and comprehensive dataset of eco-industrial parks and a dataset of food webs which is both current and ecologist approved to use for comparisons.

#### 1.2.1.2 Secondary Research Question 2 (*SubRQ2*)

Based on a better understanding of missing important ecological components and inaccuracies in the existing analogies, can a universal set of analogous food web definitions be created for use in industrial ecology?

- **Research Goal 2a)** (*SubRG2a*) Establish industry analogous definitions and usage for the basic ecological quantities species, functional groups, linkages, and matrix definition.

#### 1.2.1.3 Secondary Research Question 3 (*SubRQ3*)

What is the next step, beyond using food web structure, in the ecological analysis of industry networks?

- **Research Goal 3a)** (*SubRG3a*) Investigate the potential benefits of ecological flow-based analyses of EIPs, with a focus on the industry value of flow based information and results that cannot be obtained from a purely structural analysis.

#### 1.2.1.4 Secondary Research Question 4 (*SubRQ4*)

What makes an EIP good or bad based on the investigated ecological measures and metrics?

- **Research Goal 4a)** (*SubRG4a*) Quantitatively confirm or deny that bio-inspired network patterns lead to environmentally superior industrial network designs.

- **Research Goal 4b)** (*SubRG4b*) Identify the fundamental physical relationships responsible for the correlation seen between bio-inspired network patterns and environmentally superior industrial network designs.

- **Research Goal 4c)** (*SubRG4c*) Create EIP design guidance based on identified key ecological components, physical relationships, and quantitative reasoning found describing relationships between EIPs and food webs.

## 1.3 Contributions

This dissertation is a multidisciplinary development of ideas from biology for human design. The outcomes are reductions in environmental burdens at the systems level, defined by the EPA as energy and resource use and environmental releases to air, water, and land (Curran 2006), while simultaneously providing significant economic improvements industrial resource networks.

### 1.3.1 Primary Research Contributions

- **An in depth understanding of the impact that complex internal cycling has in the structure and functioning of food webs and how it can be used to achieve a similarly successful bio-inspired industrial resource network.**

This work establishes decisively that the conventional wisdom, that biologically inspired network design looks like "waste equals food" and that linear food chains are a poor representation of the wealth of design knowledge available from ecosystems. This dissertation overturns this conventional wisdom through an in depth investigation into the behavior and response of the important food web metric cyclicity - a metric that embodies the web like structure and cycling of ecosystems. The structural metric cyclicity is shown to be influenced by the functional relationships in food webs. These functional relationships are represented by cannibalistic behavior, omnivory, detritus, and specialization amongst participating species. It is shown here that maximization of cyclicity alone is not enough to ensure success for an EIP, as both industrial networks with higher and low cyclicity (high cyclicity being characteristic of food webs) have failed. The maximization of cyclicity and the inclusion of system actors that mimic the basic functions represented in food webs however do contribute to the achievement of the innate efficiency, sustainability, and robustness of ecosystems. This is the first time ecosystem cyclicity and its impact on industrial networks has been investigated to such a depth and degree. A secondary contribution of this investigation is, for the first time, functional groups are viewed in terms of their relative importance to structure for use in industrial resource networks.

- **The presentation of an innovative two-step optimization approach for designing bio-inspired industrial resource networks that meet industry requirements to reduce costs and emissions.**

The approach used here breaks from the previously limiting engineering approach of looking at one piece of an ecosystem in isolation of the others, and studies the relative importance of ecosystem function to its structure. Through analyses of the effects of eight food web metrics on the cost and emissions optimization of an industrial recycling network, it is shown that in contrast to previous assumptions, the system can be optimally defined through the use of only four structural metrics. This novel approach is a two-step optimization that defines structure using a group of four food web metrics and then traditionally optimizes flow for this structure. When compared to the recycling network resulting from a traditional optimization alone, the biologically defined network is more robust - mimicking the robustness, efficiency, and redundancy of food webs. This is a connection and approach that, to the author's knowledge, has never before been quantitatively realized.

- **The first comprehensive development of food web metrics based on flow information for use in the bio-inspired design of industrial resource networks.**

Recent literature indicates that the use of flow based metrics might be a productive path forward in the bio-inspired design of industrial resource networks. The work here is the first comprehensive development of the use of flow-based food web metrics, and shows that the approach has real and significant value to industry. This finding is significant in that flow-based information is difficult to obtain and often proprietary and the currently available sources are severely limited. With the discovery of the valuable gains that can be presented with the use of this information, industry will be apt to aid researchers, enabling a continuation of new developments and future work in this area.

### 1.3.2 Secondary Research Contributions

- **The establishment of quantitative validation for the use of bio-inspired principles in network design.**

Using food webs for bio-inspired network design is commonly faulted for its prolific use of qualitative reasoning. The research in the area has not addressed the need to quantitatively validate bio-inspired principles using science and engineering. This lack of a quantitative foundation is the most essential step in the understanding and wide-spread use of ecosystems for industrial network design. This study remedies this gap in the field by elucidating a positive relationship between two key design metrics (cyclicity and robustness) and 1st law -or- thermodynamic efficiency, creating a heretofore unrecognized relationship between the two. This shows that, in contrast to the harsh critiques of the use of bio-inspired designs, there is in fact 1st principle-based evidence of the success of this method, and these metrics in particular.

- **A collection of the most expansive dataset available of 48 eco-industrial parks for use in comprehensive food web analyses.**

Industrial resource networks must be designed with both sustainability and efficiency in mind to meet the needs of present and future generations. Food webs present designers with an excellent source of guidance. However, the diffusion of natural systems into useable design guidelines has been met with difficulties. The lack of reliable and comprehensive data has allowed for the accumulation of objective theories, limiting scientific progress in the design of sustainable industrial networks. This work contributes the most expansive EIP data set of its kind, allowing for a large scale, comprehensive food web analysis of EIPs for the first time.

- **The understanding of current ecology field-wide standards and a collection of a comprehensive food web dataset that meets those standards.**

Progress has also been limited by a lack of awareness of industry-wide policy changes to the collection and documentation of food webs. Early food web data sets are unreliable and developed for the specific purposes of each research group. When used for EIP comparisons, early data gives inaccurate conclusions regarding the biological-ness of EIPs. A secondary contribution of the work in this dissertation is the presentation of a collection of food webs whose median values represent a current depiction of food web structure and behavior. This is the first time EIPs have been consciously compared to ecologically accepted food web data.

## 1.4 Methodology: Using Nature as a Model, Measure, and Mentor

The proposed research questions and goals are answered in this dissertation by performing the following tasks (RTs):

### 1.4.1 Research Task 1

**(RT1) Build a collection of industrial case studies (EIPs) which may be used for ecosystem-based structure and flow analyses.**

A detailed and complete set of eco-industrial park case studies is a quintessential part of this dissertation. The data set is built from thorough literature reviews and internet searches as no such data set yet exists. Literature includes (but is not limited to) articles from various industrial ecology minded journals, industry media releases, conference proceedings and presentations, and reviews. Internet searches will include (but not limited to) news articles, company and EIP websites, graphics, university groups with focuses on sustainable design, EIP advocacy groups and government initiatives. Three datasets are created. The first is for those EIPs for which structural data may be found. Desirable structural information includes information on the physical linkages between companies, such as the industrial actors that are connected, and the materials and/or energy that is exchanged. Additionally, flow-based information regarding the amount being exchanged (commonly in the units of volume or mass /yr.) is desired. With the most basic structural data, information on the physical connections, structural metrics used by ecologists are applied to analyze the EIPs. Information on the material and/or energy flows across the linkages allows for additional, more complex metrics and analyses (such as an input-output analysis) to be applied to the EIPs. Unfortunately flow-based information is often proprietary and thus difficult to obtain. As such the industrial networks where flow information is available are included in a special grouping from which additional comparisons and analysis are done. The third data set provides more general information: collecting names, locations, references, brief descriptions, and when possible current status and/or proposal year. This last data set provides a better sense of the parks that exist around the world but for which detailed information may not be available.

### 1.4.2 Research Task 2

**(RT2) Collect high quality biological food webs (FWs) to use for comparison with EIPs.**

An extensive set of FWs is collected and coupled with an understanding of the different ways ecologists document FWs. These together meet the crucial task of understanding and establishing statistically significant relationships and averages. Literature referenced includes (but is not limited to) articles from various ecology minded journals, books, conference proceedings and presentations, and reviews. Food webs data sets exist in the literature and small sets have been used in the (few) previously attempted EIP-FW comparisons. The FW data sets used however have all been either too small for any statistically significant relationships to be made, for example Reap used a set of 24 FWs for cyclicity value comparisons with EIPs (Reap 2009), or they have not been in the same form as the EIPs due to a lack in understanding of the ecological methodology. Hardy and Graedel for example compared a set of industrial food web matrices [**F**] to a set of ecosystem community matrices [**C**] (Hardy and Graedel 2002). Many cases of EIP analysis have some form of both of these conditions.

### 1.4.3 Research Task 3

**(RT3) Translate and apply metrics commonly used by ecologists for describing and analyzing biological food webs to the EIPs collected.**

Ecosystems are analyzed in terms of a simplified food web representation. This representation allows key structural and functional components to be highlighted. Metrics and measures developed and adapted by ecologists quantify food web function and behavior. The application of these analyses and representation techniques to EIPs is not straightforward, as not all properties directly translate from ecosystems to industrial networks. The successful translation requires a conscious effort to understand ecosystem behavior and the methods of ecologists so that informed decisions may be made as to their industry counterparts.

#### 1.4.3.1 Research Task 3a

**(RT3a) Compare the values obtained for the EIPs and FWs collected to determine how close EIPs are to fully realizing the structure and functioning of ecosystems.**

Using median values from the FWs data sets as goals the EIPs can be evaluated with regards to how successfully they imitate their FW counterparts. The resulting distribution of EIPs created for each metric investigated gives insight into the success of the overall EIP design and the potential use of each metric as a design parameter.

#### 1.4.3.2 Research Task 3b

**(RT3b) "Species" are often an aggregated grouping in food webs. To understand the organizational decision of ecologists and the transplantation of these decisions to**

**EIPs the definition of species in EIPs must be varied. The use of functional groups in the place of species will be closely investigated in particular.**

Preliminary work that was done in this dissertation leads to the belief that how one defines species in the industrial setting can influence the resulting ecological analysis.. The impact of different FW organization methods is quantified by applying knowledge from the previous research tasks, with a focus on the different ways ecologists group organisms within a food web, to the EIP and recalculating the FW metrics.

#### 1.4.3.3 Research Task 3c

**(RT3c) Investigate the different practices used in ecology for structurally describing an ecosystem for their effect on the food web analysis of EIPs.**

Food webs can structurally be described using three different types of matrices. Changes in the ecological metrics calculated therefrom are documented to establish and track the resultant impact of the different matrices. A better understanding of the ecological decision making process and its successful translation to industrial networks results.

### 1.4.4 Research Task 4

**(RT4) Analyze ecological metrics using science and engineering 1st principles to give the results from RT3 a rigorous engineering background. This will be accomplished by relating the metric cyclicity to thermodynamic efficiency (1st law efficiency) of thermodynamic power cycles.**

The field of industrial ecology (IE) would be greatly advanced by establishing a connection to rigorously proven 1st principles. IE has been described as a qualitative design approach, with abstract theories made up of ‘concepts,’ the use of models and tools that ‘hold promise,’ and a vague definition of sustainability (Korhonen 2005, Jabareen 2008, Pierrakakis 2009). A connection is established here between the ecological approach used by IE and engineering first principles by applying ecological metrics to thermodynamic networks. The Rankine and Brayton thermodynamic power cycles are selected for use in their ideal forms. The efficiency of a thermodynamic power cycle is defined by the First Law of Thermodynamics and compared to the ecological metric cyclicity.

### 1.4.5 Research Task 5

**(RT5) A hypothesis resulting from the previous research tasks is that some metrics may be more influential in determining a biologically similar structure and the associated sustainability and efficiency of an EIP. An existing carpet recycling network model is investigated in depth to determine the effect of different food web metrics individually and in groups to find key ecological properties and metrics responsible for resultant biologically inspired designs.**

Another aspect of increasing the practicality of this work is identifying key metrics responsible for biologically inspired network structures. The biological optimization results seen by Reap for a carpet recycling network show a remarkable correlation with traditional industry optimization (with respect to financial cost and environmental burdens) (Reap 2009). The optimization however used equally weighted ecological metrics and did not go in depth regarding the individual effect each of the metrics had in obtaining the overall correlation. This study investigates if there are 'special' metrics that have a dominant effect on the resultant network structure. Each metric is isolated and used in combinations to determine it's the relative effect.

### 1.4.6 Research Task 6

**(RT6) Investigate select flow-based FW metrics for use in industrial resource network design, the next step in bio-inspired network analyses.**

The next frontier in the bio-inspired design of EIPs is using ecological flow-based analyses. This has not yet been investigated in depth for EIPs and therefore everything from basic industry definitions to the analysis process must be defined and translated to industry in much the same way as was done for the structural analyses covered here.

#### 1.4.6.1 Research Task 6a

**(RT6a) Using the thermodynamic power cycles from RT4a, apply select flow based food web metrics to establish a quantitative relationship between the metrics and engineering 1st principles.**

Following the reasoning of RT4a, the thermodynamic power cycles used there will be used again to better understand and quantify the impact of the flow based metrics investigated. The success of flow-based food web design inspiration for sustainable industrial network design will be greatly enhanced by establishing a connection to proven 1st principles of science and engineering. The efficiency of the thermodynamic cycles is compared to the flow-based metric ‘robustness.’

#### 1.4.6.2 Research Task 6b

**(RT6b) Calculate select flow-based metrics for industrial networks that have flow information available and compare these to median food web values.**

Flow based information is difficult to find in published literature and in publicly available resources. A few industrial networks were found that had published information regarding the quantities of materials and energy flowing between system actors. Flow-based metrics from food webs are applied to these select industrial networks providing a benchmark of the relative behavior of industrial networks. Median food web values for the metrics calculated are used for the comparison.

#### 1.4.6.3 Research Task 6c

**(RT6c) Apply the flow-based food web metrics investigated in the previous tasks to the carpet recycling model investigated in RT5.**

The best combination of structural food web metrics found in RT5 gave a two-step optimization for a carpet recycling model. Flow-based food web metrics are applied to the model to relate the behavior of these new metrics and analysis technique to the thoroughly investigated structural analysis done earlier.

## 1.5 Assumptions

This work acknowledges that there is some percentage error in the biological data we are using. The author is not an ecologist and will therefore use food web data as it is presented in the literature. The main assumption of this dissertation is that ecosystems are inherently sustainable. Mimicking their behavior, it is assumed, will bring industry closer to the sustainable functioning of nature. The validity of this assumption is based on previous work done by Reap showing a relationship between a traditionally optimized carpet recycling network (optimized using cost and emissions) and the same carpet recycling network designed to mimic the structure of food webs (Reap 2009) also (Mayer 2008).

All systems analyzed in this dissertation are done so assuming them to be operating at steady state. EIPs are viewed here on a spatial scale as opposed to temporal, and only the exchanges of materials and energy in the system are addressed, to the exclusion of services.

Most of the literature on food webs states that, if anything, the collections and analyses that have been done on food webs underestimate the complexity and density of both the types of species represented and the interactions. Thus we may assume that the average values for food webs used here as goal values for the industrial networks are most likely low estimates of the actual performance, and therefore reasonable goals.

## 1.6 Dissertation Layout

This dissertation covers a range of topics regarding the analysis of industrial resource networks using biological practices and principles. Following this introduction, a thorough literature review covers the current state of bio-inspired industrial networks, or eco-industrial parks (EIPs). Covered are the major findings, errors, and limitations in their creation and function. The literature review also goes in depth into the field of ecology and the study of food webs as this is the design inspiration. Highlighted in the review is one of the largest problems in biologically analyzing EIPs: a basic misunderstanding of food webs. Because of this, and as ecology is not the main field of this dissertation, the literature review extends all the way back to the basics of ecosystems – the networks that food webs are meant to model.

Building from this foundational description of food webs and their ecosystem counterparts, commonalities and differences between food webs and EIPs are laid out. Many of the misconceptions found in the literature review concern industry definitions for ecological terms. Thus, particular attention is paid to the establishment and editing of these basic analogies. With this foundation for the analogy between industry and ecosystems created, the methods for building and analyzing food web models are laid out for their use on EIPs.

The literature review also showed a need for a quantitative understanding of design guidelines resulting from food webs. This dissertation uses first principles to aid in explaining characteristic results of food web analyses. Thermodynamic power cycles readily lend themselves to the job: like EIPs and FWs, a power cycle is composed of directionally-constrained interacting components that transform an internal flow. The food web metric cyclicity, a measure that showed itself in the literature review to be very important to the definition and workings of food webs, is applied and explained using 28 thermodynamic power cycles of increasing complexity. The result is cyclicity is related to and explained using thermodynamic- or first law- efficiency.

With the methods and metrics translated and understood using an engineering reference point, food web structural analyses are applied to a collection of 48 EIPs, collected here using literature reviews, news searches, and online company investigations. The results of the EIP analyses are compared to values from a set of 142 food webs complied here using similar in depth searches. The techniques used to create the food web models from ecosystems are explored for their ability to similarly organize complex industrial networks into simple structural representations. Behavioral differences between the food webs and the EIPs are highlighted and the relationship in industry between system size and ecological success is tested. Important functional groups within food webs are investigated in terms of analogous industry groups. The potential effects of singularly industrial characteristics, such as proximity between companies and the presence of agriculture within the system boundaries, are investigated in terms of their effect on meeting food web standards. The complex structural cycling that is prized in food webs for the resultant efficient use of resources and structural stability are also prized characteristics for industrial networks. The food web measure for structural cycling is called cyclicity and is examined to add to the quantitative understanding gained from the thermodynamic analysis. The presence and strength of internal cycling and the last known status of the EIPs are used as ranking criteria, separating the 48 EIPs into three groups and four classes. The EIPs are organized and ranked with the goal of finding patterns based on the ecological information.

The next step in using food webs to design and analyze the sustainability of industrial resource networks is to use flow-based food web metrics in a similar fashion. A set of flow-based metrics are translated for their use on industrial networks and then applied to a few industrial networks for which volumetric flow information for the interactions between system-actors was available. Again similar to the structural metrics, a quantitative analysis of the flow based metrics *robustness* is done using thermodynamic power cycles. The quantitative understanding is used to explain the variations in robustness values seen for the food webs and different types of industrial networks.

All the information and understanding gained from both the flow and structural food web analyses are applied to a carpet recycling network model. The model tests a previously found correlation between a traditionally optimized network, i.e. based on cost and emissions, and a biologically inspired network design. The original biological model weighted eight different food web metrics equally, with no investigation into the relative effect of each metric. A methodical approach looks at each metric individually and an exhaustive variety of combinations of the metrics. The result is a “best combination” of four structural metrics. The four metrics used together create a structure that best mimics food web structure. Using this structure an optimization of the volume of flows moving across each connection is done using traditional optimization techniques to reduce the total network cost and emissions. This two-step approach is presented as a proposed sustainable design technique for industrial resource networks. Flow metrics are also investigated for the different network setups, showing the results of a flow analysis on the model when a traditional optimization is done as compared to the proposed two-step approach.

The dissertation is concluded with a summary of the work done. The findings are summarized and proposed future work stemming from the findings is suggested.

## 1.7 Summary

Is biological inspiration, in the form of ecological network patterns, principles and metrics, a quantifiably preeminent route for optimizing industrial resource network designs? This is the research question proposed by this work, composed with the goal of understanding the behavior of the natural ecosystems that inspire the design of sustainable industrial networks. The overarching goal and question are answered through the completion of a series of tasks outlined that explore the analyses of food webs and how they may be applied to industry. The completion of these tasks results in a set of primary and secondary research contributions that significantly impact the success in designing a sustainable industrial resource network. The primary contributions of this work are:

1) An in depth understanding of the impact that complex internal cycling has in the structure and functioning of food webs and how it can be used to achieve a similarly successful bio-inspired industrial resource network.
2) The presentation of an innovative two-step optimization approach to the design of bio-inspired industrial resource networks that also reduce cost and emissions.

3) The first comprehensive development of food web metrics based on flow information for use in the bio-inspired design of industrial resource networks.

A number of secondary contributions to the sustainable design process were also formulated in the process of completing this dissertation. The following eight chapters cover the range of this work, from a literature review through to the discovery of a two-step optimization procedure for designing industrial resource networks to mimic the structure and functioning of food webs. This work ends with a proposal of a number of ideas for future work building from the work done here.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Closed-Loop Sustainable Industrial Chains and Re-X Networks

All products and processes affect our environment during their life span. Materials are mined from the earth, air and sea, processed and manufactured into products on vast industrial estates, and then distributed over thousands of miles of air, land and water to consumers, as represented by the flow from left to right in the top half of Figure 1. The issue is at the end of this chain, when the products are no longer used or wanted. In 2009 over $700 million worth of operational computer network equipment was destroyed (Guide and Van Wassenhove 2009). China in 2009 instated the ‘Circular Economy Law’ with the goal of developing a recycling economy, for example requiring the industrial implementation of water-saving technologies and waste and byproduct reuse (Mathews and Tan 2011). Legislations and directives such as these have created initiatives for product take-back and demanufacture (Ji 2008), resulting in closed-loop manufacturing and a focus on a products entire life cycle (Figure 1, entire cycle), a stark contrast to the standard linear network chains (Figure 1, top half). These take-back initiatives extend beyond the final product to ancillary flows as well. The result of all these measures has been a complete reorganization of industrial networks into closed-loop supply chains (CLSC). CLSC have economic, social, and environmental benefits (Ji 2008). Economically the overall cost of the supply chain is reduced through increased efficiencies, reduced scare resource use, and designs in line with recovery processes. A positive correlation was found between the adoption of environmentally-friendly strategies and performance improvements with respect to other same-sector firms (Claver, Lopez et al. 2007, Fath). Shared recycling networks reduce waste treatment and disposal costs for each company involved (Desrochers 2004). Social feelings towards companies who embody ‘green thinking’ tend to be more positive, inciting greater customer loyalty and satisfaction, which leads to an increase in overall sales. In the United States it is estimated that purchasing decisions of 75% of consumers are influenced by a company's environmental image, and 80% would be willing to pay more for the same good if they felt it was environmentally friendly (Lamming and Hampson 1996). Using recovered products through recycling and reuse has been shown to reduce energy and water consumption and waste emissions (Clift and Wright 2000, Ji 2008). The remanufacturing sector in the late 90's saw annual sales in excess of $53 billion (Lund 1996). Chertow and Lombardi present what they state as "clear evidence" of the substantial economic and environmental benefit to inter-industry exchanges of materials, water and energy (Chertow and Lombardi). Financial winners may seem lopsided at first, however those that are not necessarily monetary winners do not leave these relationships empty handed. Requirements to operate for industries, such as those in areas with water scarcity who may have water limits imposed, can be successfully met through closed-loop relationships. The growing demand for these nonlinear networks leads one to the overarching questions this dissertation seeks to answer: *'How should these networks be designed, and where might one look for innovative examples?'* The solution may lie in the structure and characteristics of food webs, which have formed a biological framework for transitioning from open to closed-loop manufacturing networks. Focusing on the architecture of the layout of these systems, rather than redesigning the products and processes within them such that the waste is and can be reused, is a more viable solution that is much more likely to be implemented by companies (Frosch 1992).

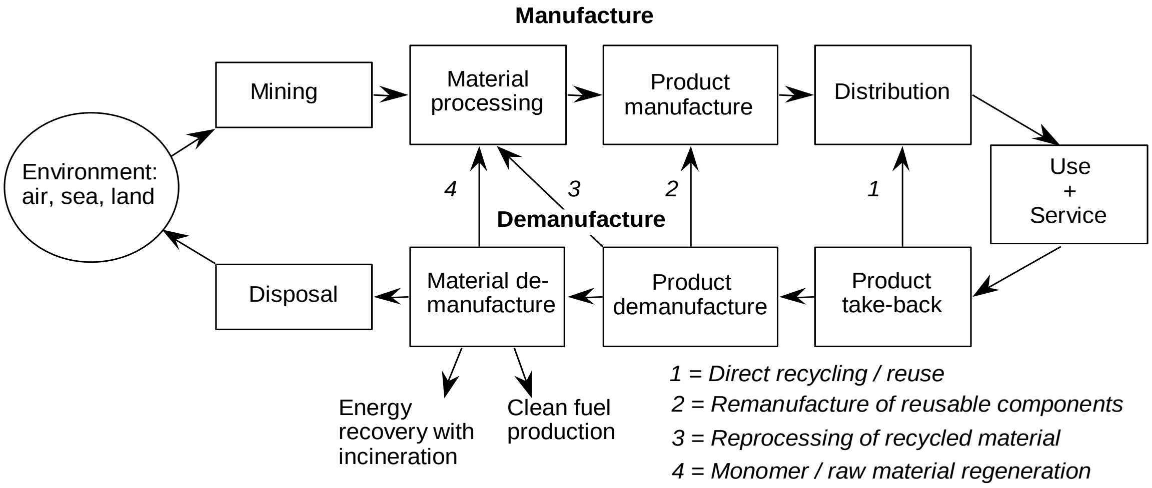


Figure 1: A Generic Representation of a Product's Life-Cycle. *Figure from* (Bras 1997).

## 2.2 Graph Theory

Graph theory is used by ecologists to mathematically describe the structure and flow of the food webs studied. The following definitions come from (Roberts 1976). Graph theory uses graphs described by sets of vertices and arcs to describe a network. A *directed graph* or *digraph* is made up of *nodes* or *vertices*, *points*, *etc.* that together make up a set of vertices and are connected by *arcs* or *links*, *arrows*, *directed lines* or *edges*, *curves*, *etc* that make up a set of directed arcs. The descriptor '*directed'* is used to differentiate from a *graph,* where links that have no direction specified and travel may occur in either direction across a directionless *edge*. The work throughout this dissertation uses *directed links* and therefore *digraphs* are used whether or not it is specified. An example of a simple digraph is shown in Figure 2.The placement of and the distance between the vertices and t nature of the lines adjoining them is of no particular importance. Any crossing points of the lines connecting vertices are not necessarily a vertex. All of the information in a digraph is contained in the existence or absence of connection between two vertices and the direction of said connection.

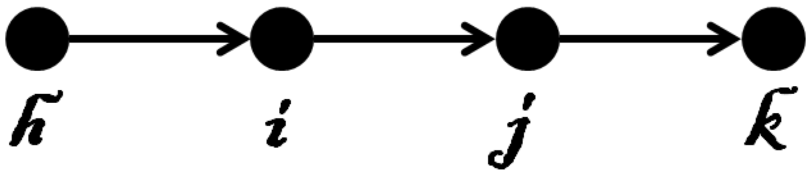


Figure 2: A hypothetical example of a simple directed graph or a digraph. The set of nodes or vertices is described by {h,i,j,k} and the set of arcs or links is described by {(h,i), (i,j), (j,k)}. *Figure adapted from (Roberts 1976).*

A *path* from node *h* to *k* in Figure 2 represents a sequence of nodes and arcs leading from *h* to *k* described by the series $\{(h,i),(i,j),(j,k)\}$. *Path length* is the number of arcs in a path, thus for the preceding path example from *h* to *k* the path length would be three (3). Another description is the number of times input flows provide functional value to the system (Reap 2009). A *closed path*, also termed a *cycle*, is one which starts and ends at the same node (Patten 1985). If the digraph in Figure 2 had a link from *k* to *h* then there would be a cycle centered on any of the nodes *h* through *k*. A cycle of length one (1) is termed a *self-loop*. A *simple cycle* or a *simple path* is defined where within a path no node is visited more than once, so for a digraph with *n* nodes, the longest simple path in the digraph is of length *n*. A *compound path* is one where any and all nodes are repeated along the path.

Often it is convenient to summarize and analyze the information contained in a digraph or graph in matrix form. Food web digraphs are often represented by a *community matrix*. A community matrix [**C**] is a square matrix whose rows and columns represent the nodes of a digraph and the entries, ones or zeroes, represent the links. An entry of *one* in an community matrix in $c_{ij}$ signifies that a link exists from *i* to *j* and an entry of *zero* in $c_{ij}$ represents no link. To remind readers, *i* in $c_{ij}$ represents the row position and *j* in $c_{ij}$ represents the column position. The transpose of the community matrix is known as the adj*acency matrix* [**A**] and results in an orientation of flow from columns to rows (*j* to *i*). An adjacency matrix is always non-negative because all entries are greater than or equal to zero. When the adjacency matrix is raised to the power *l*, the product matrix $[\mathbf{A}]^l$ gives the number of paths, simple and compound, of length $l$ from all $j$ to $i$. This is proven by Theorem 2.11 in the book *Discrete Mathematical Models: with applications to social, biological, and environmental problems* by Fred S. Roberts (Roberts 1976). A path of length *two* (2) between $i$ and $k$ exists in the hypothetical digraph of Figure 2 and is given by a *one* (1) in the position $a_{ik}$ in the $[\mathbf{A}]^2$ product matrix. This documents that $i$ and $k$ are connected by a single common node $j$ with a path of length *two* (2) from $i$ to $j$ to $k$. The number of paths of length $l$ would be calculated by $\sum[\mathbf{A}]^l$. The rate of increase of number of paths as the path length increases is known as *pathway proliferation* (Borrett, Fath et al. 2007). A succinct estimate for the pathway proliferation rate is the maximum real eigenvalue, or *cyclicity*, of the adjacency matrix. Using this method, digraphs may be classified as one of three types: strongly connected, weakly connected, and disconnected. If any node may be reached from any other node over a pathway of any length then the digraph is strongly connected, if the same is possible only if link orientation is ignored (direction of the specific path) then the digraph is weakly connected. If neither of these two scenarios is possible the digraph is said to be disconnected, this often takes the form of non-adjacent strong or weak components within the overall digraph. A digraph with strong structural cycling will have a maximum real eigenvalue greater than one, a digraph with basic structural cycling will have a maximum real eigenvalue equal to one, and a digraph without any cycles will have a maximum real eigenvalue equal to zero. Because the adjacency matrix A is binary, the maximum real eigenvalue cannot take values between zero and one. The pathway proliferation rates of these three types of digraphs, as $l \rightarrow \infty$ are summarized by Borrett *et al*. as follows (Borrett, Fath et al. 2007):

(1) If $\lambda_{max}(\mathbf{A}) = 0$ (a digraph where no cycles exist) then the number of pathways between any two nodes will decline to zero.

(2) If $\lambda_{max}(\mathbf{A}) = 1$ (a digraph where at least one simple cycle exists) then the number of pathways between nodes in a strongly connected component within the digraph will remain constant.

(3) If $\lambda_{max}(\mathbf{A}) > 1$ (a digraph where more than one simple cycle exists) then the number of pathways between nodes will increase without bound at an asymptotic rate equal to $\lambda_{\max}(\mathbf{A})$.

Network models in graph theory have been used to model social networks, where the nodes represent individuals and the links may represent a social relationship between individuals (Wasserman and Faust 1994, Newman 2001), the World Wide Web, where the web pages are nodes and the links between them are hyperlinks (Albert, Jeong et al. 1999, Barabási and Albert 1999), and by ecologists to represent trophic relations in food webs or energy-matter fluxes in ecosystems (Margalef 1963, Pimm 1982, Cohen, Briand et al. 1990, Higashi and Burns 1991, Brooks 2006). The ecological interest in using graph theory is in tracing one species or set of species to another through a chain of predators. Due to the geometric point of view of digraphs the definition of various structural concepts is possible. All of the structural metrics used by ecologists are based off of a digraph.

### 2.3 Design Inspiration: Ecosystems and Food Webs

"The simplest question one can ask of a food web is how connected it is" (Pimm 2002).

Ecosystems comprise a category of organization in ecology which looks at the pathways of energy and matter, thus organic and inorganic material flows, which move among living and nonliving elements. *Ecosystems* encompass a community, as described by the interactions between populations of species, together with its physical environment (Townsend, Begon et al. 2008). *Food webs* tend to have smaller system boundaries and are used by ecologists to describe and quantify the complexity of ecosystems by way of the biotic interactions among the inhabiting species, "who eats whom" (Borrett, Fath et al. 2007, Halnes, Fath et al. 2007, Bascompte 2009). Food webs capture biodiversity, species interactions (particularly feeding relationships), and the structure and direction of relationships (e.g. between predators and prey). A food web in its most basic mathematical sense is a directed graph (or *digraph*) showing the directional relationships between objects (Roberts 1976, Fath and Patten 1999). The objects in a food web are the species, and the relationships are the flows of materials and energy; in an ecosystem this is between predators and prey (Pimm 2002).

*Predators* are the consumers in an ecosystem. They obtain their energy directly by grazing, feeding on other animals (usually of a single species or a narrow range of closely related species), or both (Husar 1994, Korhonen and Snäkin 2005). Predators fall into two categories, specialists and generalists. *Specialists* tend to make up a smaller portion of the systems as they interact with very particular prey, making them more susceptible to of system fluctuations (Bascompte, Jordano et al. 2003, Bascompte and Jordano 2007, Thebault and Fontaine 2008). *Generalists* feed on wide variety of prey and therefor are more easily supported by the system. The wider variety of feeding options results in a high degree of connectedness between generalists and the rest of the system. Generalists provide a robust backbone to the system that allows for rare species and specialists to exist, resulting in the asymmetric structure characteristic of ecosystems (Bascompte, Jordano et al. 2003, Bascompte and Jordano 2007). *Asymmetric structure* can be summarized with the following scenario: if species A is highly dependent on species B, then species B is weakly dependent on species A (Bascompte, Jordano et al. 2006). A high degree of asymmetry in food webs, specifically networks characterized by mutualistic interactions, has been linked to enhanced long-tern coexistence and the maintenance of biodiversity (Bascompte, Jordano et al. 2006, Vazquez, Melian et al. 2007). *Prey* are consumed by predators, providing the sustenance required for the system to exist and thus are the “producers” of the system. At the most basic level are the primary producers, which are capable of producing their own food using photo- or chemical- synthesis (plants and some bacteria) (Husar 1994, Korhonen and Snäkin 2005).

A *species* in a food web is defined as  a group of organisms (an individual biological entity (Husar 1994, Townsend, Begon et al. 2008)) that share a common gene pool and have a unique evolutionary history distinct from other groups of organisms (2005). The genetic continuity is important because it makes species an evolutionary unit such that all members of a given species share the same requirements for life. Requirements for life, or the set of conditions an organism requires to live, are organized by ecologists into *niches*. An organism's niche may also be defined by its functional role in the community (Leibold 1995). Ecosystems can be extremely large systems, thus for the purpose of analysis species in an ecosystem are commonly aggregated in terms of trophic levels, niches, or functional groups. *Trophic species* are defined as functional groups of taxa which share some set of predators and prey and is the most common species aggregator used (Dunne, Williams et al. 2002, Allesina, Bondavalli et al. 2005, Fath 2007, Bascompte 2009). Trophic groupings relate to the feeding habits of the organisms in the food web (Fath 2007). *Trophic groups* consist of plants (the primary producers of an ecosystem), heterotrophs (consume plant material or other heterotrophs), herbivores (organisms adapted to feed on plants), carnivores (consume animal tissue through predation or scavenging), decomposers (decompose organic matter into inorganic substances that can be reused as input for plants), and detritivores (consume dead matter). Ecologists may also employ *trophic levels*: the first are the primary producers (plants), the second are the primary consumers (heterotrophs and herbivores), and the third are the secondary consumers (carnivores) (Husar 1994, Korhonen and Snäkin 2005). *Functional groups*, very similarly to niche (Leibold 1995), are based on the response of species to their environment or the effects that a species has on the systems processes (Gitay and Noble 1997). There are numerous approaches to ecosystem documentation and organization so their definition is often a reflection of the knowledge of the organisms and ecosystems being addressed (Hooper, Solan et al. 2002).

There are many aspects of food webs that are of great interest to the design of networks. The stability and robustness of an ecosystem may be influenced by everything from the diversity in the system, the presence of omnivory and mutualistic interactions (Heymans, Ulanowicz et al. 2002). As a result all of these features are outlined here so that they may be understood and useful aspects may potentially be transferred into the tool kit of industry designers. Ecosystem robustness and stability are heavily investigated system properties. *Robustness* is defined as when the system and its relationships are able to remain roughly the same in the face of larger disturbances (Townsend, Begon et al. 2008). Robust ecosystems tend to survive when affected with random extinctions or species removals but are susceptible to deliberate removals. A result of their structure is that robust ecosystems tend to rely on a few well-connected species that act as “glue” – if these key species disappear the entire network would be expected to collapse quickly (Bascompte 2009). Network robustness can be measured as a fraction of the species that must become extinct for the resulting network to fragment into several disjointed species (Albert, Jeong et al. 2000, Dunne, Williams et al. 2002, Allesina and Bodini 2004, Bascompte and Jordano 2007). Ecosystem *stability* is enhanced by avoiding strong interactions in long loops or in successive levels of tri-trophic food chains (when three trophic levels are connected to each other directly) (Bascompte and Jordano 2007). Stable ecosystems have the tendency for perturbations in the population to damp out, returning the system to some constant configuration (Hardy and Graedel 2002). on The connection between stability and diversity have sparked many debates within ecology (May 1972, May 2000, McCann 2000),

Debates over the influence of the presence and strength of omnivorous interactions on the stability of the system are also numerous both for: (Fagan 1997, Neutel, Heesterbeek et al. 2007, Ispolatov and Doebeli 2011, Kratina, LeCraw et al. 2012) and against: (Pimm and Lawton 1978, Pimm 1979, Ispolatov and Doebeli 2011, Gellner and McCann 2012). When a species feeds on more than one trophic level (plants and animals), resulting in a diet consisting of a variety of food sources, it is known as *omnivory* (Bascompte 2009). Regardless of the winning side of the debate, omnivory plays a key role in the structure and function of ecosystems and any effect it has on system stability is of great interest. Omnivory forms an important part of the structural foundation of food webs, allowing for the multi-directional passage of resources that helps ensure robust communities. Figure 3 shows a simplified food network in an aquatic system with prominent omnivory. The figure highlights the widespread feeding that characteristically occurs across multiple trophic levels in these types of systems.

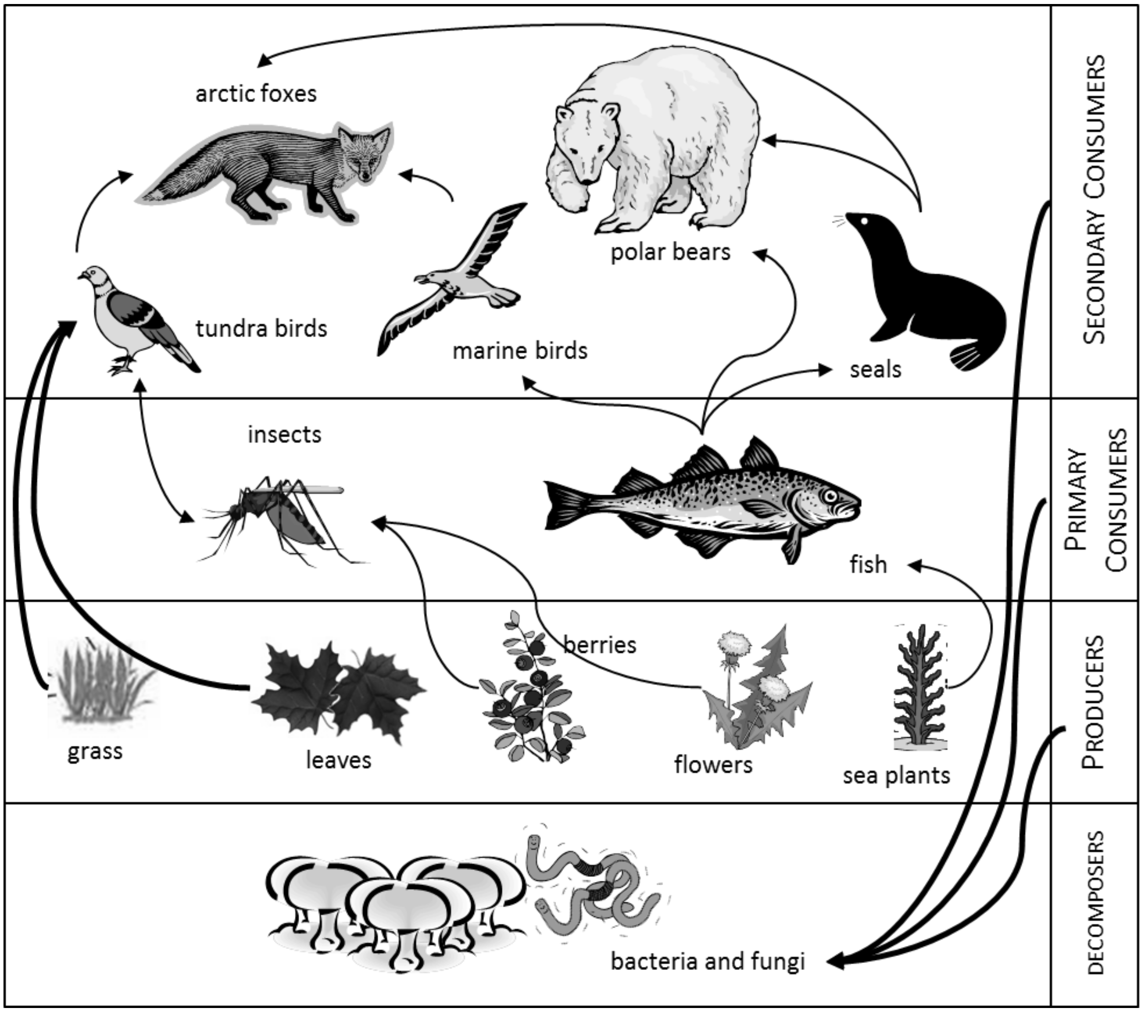


Figure 3: A food web in an arctic system highlighting interations that occur across multiple trophic levels. Connecting arrows point to the consumer.

Mutualism is another interesting interaction found in ecosystems that may affect the maintenance of diversity, thereby affecting stability and robustness. Mutualism is a an interaction that is beneficial to both participating parties, resulting in a relationship in two directions. An example of a mutualistic interaction would be between plants and their animal pollinators and seed dispersers: often one of the interactions is in the form of a provided service. Closely tied to asymmetric network structures, mutualistic interactions are often between specialists that interact only with generalists, this results in fewer fluctuations and a core group of species which drive the system (Bascompte, Jordano et al. 2003). Due to the strong influence that mutualistic interactions have on an ecosystems structure, mutualistic networks have been termed “the architecture of biodiversity” (Bascompte and Jordano 2007).

### 2.3.1 Food Web Analyses in the Ecological Community

“Food webs are not sophisticated,” Pimm states in his book titled *Food Webs* (Pimm 2002). There is no consistent approach for determining system boundaries (Halnes, Fath et al. 2007). They are not “built on excellent data” and the linkages recorded are “less often based on experimental evidence than on casual observations (Pimm 2002).” The represented species have in most cases, been either highly aggregated or represent small part of the whole system (Fath, Scharler et al. 2007, Gross, Rudolf et al. 2009). The lack of connections to the detritivores and decomposers as a group has been pointed out by numerous publications (Moore, Berlow et al. 2004, Allesina, Bondavalli et al. 2005, Fath, Scharler et al. 2007, Halnes, Fath et al. 2007), in some cases they have been added after the fact because of the well-known significance they hold in determining system structure and function (Fath and Halnes 2007). The literature covers a range of different methods for species aggregation (Krause, Frank et al. 2003); however, as with other collection and recording techniques there has been no one consistent method used across the board. The observer’s biases are often dramatic and/or expose a vertebrate-centered view of ecosystems (Pimm 2002). A sentiment expressed by the ecological community is the problem of *where to stop drawing connections*. Despite these biases and imperfect data, the evidence overwhelmingly rejects the patterns found in and between food webs being artifact (Pimm 2002) except (Closs, Watterson et al. 1993). It is prudent to note thought that for almost every publication on a pattern and relationship describing food web network behavior, there are an equal number of publications in disagreement.

#### 2.3.1.1 Shift in Food Web Data Collection Techniques

The early 1990's saw a huge shift in the perception and practice of ecosystem data collection in the field of ecology (Dunne 2006). Greater emphasis has been placed upon the quality of food web data since the early 1990's as discussed earlier (Martinez 1991, Polis 1991, Cohen, Beaver et al. 1993). In 1991 an article was published comparing characteristics in a desert ecosystem to generalized characteristics of ecosystems that had been cited up to that point (Polis 1991). The article found that properties in a desert ecosystem were all in stark contrast to those theoretical predictions and empirical generalizations that had been derived from the available catalogs of food webs at the time. The major conclusion was that actual food webs are significantly more complex than those cataloged up to that time, to the point that Polis described them as "caricatures of actual communities (Polis 1991)." Omnivory, cannibalism, and loops were commonly found, the system had a high connectivity, and top predators were not found. Chain lengths were found to be long when previously it had been assumed that food webs had short chain lengths of approximately 3-4 links (Pimm, Lawton et al. 1991). The ratio of prey-to-predators was also found to be greater than 1.0 when previously it was believed to be constant at 0.8819 (Cohen 1977, Cohen 1978, Briand and Cohen 1984).

A hypothesis amongst ecologists in the early 1990's was that many patterns observed in food webs were artifacts of a high level of aggregation of species in the data collected. This was tested and confirmed for all structural properties except connectance and predator-prey ratio, which were less sensitive than other metrics (Martinez 1991). Similar aggregation results were found by other ecologists (Schoenly and Cohen 1991), but as described earlier for every relationship there is work showing the reverse and so conflicting results were also published (Sugihara, Schoenly et al. 1989, Hall and Raffaelli 1991). The methods used in the generation of the conflicting results are suspect as noted by Dunne (Dunne 2006). The scale dependence or independence of food web network properties is another ongoing debate, with researches on both sides: dependence e.g. (Schoener 1989, Polis 1991, Martinez 1994, Martinez and Lawton 1995, Camacho, Guimera et al. 2002, Dunne, Williams et al. 2002, 2006) and independence e.g. (Cohen and Briand 1984, Sugihara, Schoenly et al. 1989, Havens 1992, Williams and Martinez 2000). Most of the debates have resulted from inconsistencies and poor techniques in data collection and analysis, something addressed in a 1993 publication by 24 top food web researches (Cohen, Beaver et al. 1993). The group effort resulted in suggestions for a variety of ways to improve food webs, specifically with a focus on better data collection. This sentiment was reiterated in other works around the same time e.g. (Havens 1992). There is still however no universally correct or uniform way to collect food web data and as such the data will always represent some biases of the collectors (Dunne 2006). The hope is that attributes and generalities will emerge when the focus is removed enough from biased collection details (Dunne 2006). Users are still cautioned by ecologists that generalities and universalities found for food webs may be artifacts of poor information due to limited data quality and supply (Lawton 1989, Dunne 2006). New interdisciplinary work and careful development of ecosystem network data support ecosystem research despite these warnings and disagreements. This stronger backbone along with an urgent need to understand environmental perturbations, biodiversity loss, and species invasions, as well as a continued desire to understand general structural patterns continues to motivate breakthrough research in the area of ecosystems structure and function (Dunne 2006).

### 2.3.2 Ecosystem Network Analysis

Ecosystem Network Analysis (ENA) is a specific type of network analysis, which is used as a tool for identifying and quantifying direct and indirect effects within a system by following flows and transactions of a consistent currency (Ulanowicz 1986, Fath and Patten

1999, Bodini and Bondavalli 2002). ENA specifically addresses the connectivity of ecosystem components by following the transfer and processing of energy and matter. Using ENA ecologists have studied the efficiency energy usage in ecosystems, major constraints existing curbing the maximum efficiency that ecosystem may obtain, and consequences for ecosystems regarding their potential for development and their ability to maintain their structure and functions during periods of stress (Bodini and Bondavalli 2002). The foundations for applying network analysis to ecosystems were introduced by Hannon and Patten (Hannon 1973, Patten 1978). These foundations are what further developed into ENA, also known as 'network environ analyses,' years later (Ulanowicz 1986). The basis for all of these analyses is graph theory and input-output analysis, which looks at the interdependence of industries in an economy (Leontief 1936). The development of ENA and its application to EIPs is illustrated in Figure 4 and shows the cyclic nature of inspiration: the analysis of industry as an economy inspired how ecologists analyzed the environment, which has then lead back to inspiring how to analyze industry systems on a smaller scale.

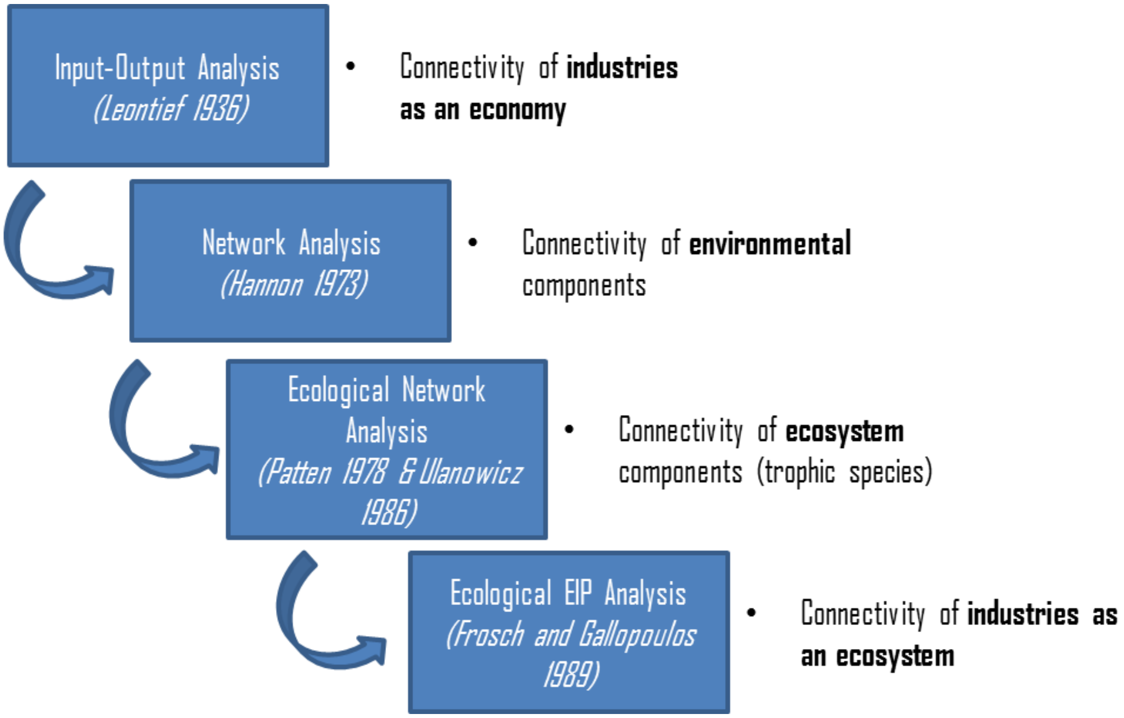


Figure 4: Timeline of the evolution of ecosystem network analysis

ENA works from three angles: behavior, structure, and function. Structure is determined by the connections between relative components in the ecosystem. Function in an ecosystem is not defined by purpose as in other disciplines, but by the process of exchanging energy and materials. Structure and function relate at a lower level to produce behavior which is expressed at a higher level in the system (Patten 1978). Thus by understanding structure and function, the behavior of the system can be anticipated, a very useful tool for all systems, both natural and man-made.

The concept of species is fundamental to ecological analysis as it provides an organizing principle for an otherwise highly complex system, grouping organisms with very similar requirements together. ‘Species’ becomes a unit of analysis under the assumption that each ‘individual’ in said grouping is considered roughly equal.  If we wish to apply ecological principles to industry and engineering, we need to use species in industrial analyses in a way that is functionally equivalent to its use in natural ecology. This presents a problem for industrial ecology since there is no obvious analogy for genetic relatedness, or at least not one that has yet been proposed.

### 2.3.2.1 Measuring Food Web Network Structure: Matrices and Metrics

Organizational matrices are used by ecologists to collect and document the exchanges between species or functional groups within the community being investigated. These matrices document a range of interactions at various levels, anything from a highly focus documentation of the predator-prey exchanges to a broad documentation of all interactions in a community. Interactions may include competition interactions, mutually beneficial interactions (mutualistic), cannibalistic interactions, and indirect interactions to name a few. The choice as to what level of detail is included is one of the collector/documenter.

Ecologists use multiple structural measures and metrics from graph theory to quantify the characteristics of food web. Extensive ecological literature defines metrics that examine ecosystem properties and species interactions see e.g. (Odum 1969, Yodzis 1980, Pimm 1982, Briand 1983, Ulanowicz 1986, Briand and Cohen 1987, Schoener 1989, Warren 1990, Cohen, Beaver et al. 1993, Husar 1994, Heywood 1995, Ulanowicz 1997, Purvis and Hector 2000, Bodini and Bondavalli 2002, Dunne, Williams et al. 2002, Fath 2007, Fath and Halnes 2007, Buzhdygan, Rudenko et al. 2010). These metrics have been developed since 1969, when Odum proposed a set of eco-indicators to estimate ecosystem maturity (Odum 1969), to understand the link between structure and behavior of these ecological systems. The metrics used measure things such as the number of species within the system boundaries, the number of links between said species, the density of links within the system, the ratio of actual links to total possible links, and the existence and strength of materials and energy cycling within the system. These methods and metrics are covered in detail later in sections 3.3.

Much of the literature on the analysis of food webs deals with coupling together different structural metrics to give insight into the dynamics, robustness, and stability of food webs e.g. (May 1973, Loreau 2000, May 2000, McCann 2000, Allesina and Ulanowicz 2004, Melian and Bascompte 2004, Rooney, McCann et al. 2006, Neutel, Heesterbeek et al. 2007, Mouillot, Krasnov et al. 2008, Gross, Rudolf et al. 2009, Ings, Montoya et al. 2009, Buzhdygan, Rudenko et al. 2010, Gellner and McCann 2012, Kratina, LeCraw et al. 2012, McCann 2012). These analyses all adhere to the assumption that “form [i.e. structure] follows function” a core idea articulated by architect Louis Sullivan and reiterated for ecosystems (Strogatz 1991); by understanding the structure of food webs their response to different types of environmental stressors may be better understood and ideally predicted (Strogatz 1991, Loreau 2000, Post, Pace et al. 2000, Tylianakis, Tscharntke et al. 2007, Fortuna, Stouffer et al. 2010, Thompson, Brose et al. 2012). For food webs, stressors are most often in the form of species extinction and other global changes (Dunne, Williams et al. 2002, Bascompte 2009, Bascompte and Stouffer 2009, Dunne and Williams 2009). Interest in food web system structure has led to an interest in other structural characteristic of the network organization such as species modularity and nestedness (Olesen, Bascompte et al. 2007, Fortuna, Stouffer et al. 2010).

### 2.3.3 Indirect Effects

A direct relationship is formed between two adjacent participating actors. An indirect relationship is formed if the actors are separated by some distance, whether physically (by one or more other actors) or by time (Higashi and Patten 1989). The desire to establish physical design guidelines in this dissertation directs our focus to the effects of physical separation. The characteristic cycling of materials and energy in food webs is one of the most desirable properties to sustainably minded industry networks. The ecologists Salas and Borrett found that in a set of 50 food webs, when significant cycling was present indirect flows were nearly always found to dominate direct flows (Salas and Borrett 2011). This and other literature over the last 20 years has established the dominance of indirect effects in ecosystems (Higashi and Patten 1989, Wootton 1994). The apparent relationship between cycling in the system and indirect effects makes it a design property of interest for industry.

Indirect effects can be determined by looking at paths of length greater than one. A path is the route traced by following some quantity of material or energy and is made up of either chains or cycles. A path with a length greater than one indicates that the material or energy being followed interacts with more than two actors in the system. The two methods for path formation are chains and cycles. Both methods limit flows through transfer efficiencies relating to dissipation and export and chains apply an additional limitation by way of their length (Borrett, Fath et al. 2007, Borrett, Whipple et al. 2010).

Graph theory enables the calculation of the number of paths of different lengths in the system by raising the adjacency matrix [**A**] to a power that represent the path length being investigated (Roberts 1976, Patten 1985). Thus $[\mathbf{A}]^4$ gives all of the paths in the network represented by [**A**] that have a length of four. This can also be done for what is known as the *flow intensity matrix* [**G**]. The flow intensity matrix highlights the amount of flow (kg, kJ, units, etc.) that is indirectly circulated through the system (circulated using paths of length greater than one).

A number of distinct patterns have arisen from the investigation of indirect effects in ecosystems. The tendency for the number of paths to increase geometrically without bound as path length increases, known as *pathway proliferation*, was first applied to the study of ecosystems  in the early 80’s (Patten, Richardson et al. 1982, Patten 1985, Patten 1985) and has been studied more recently in food webs (Borrett, Fath et al. 2007, Fath and Halnes 2007). Pathway proliferation only occurs if there is more than one cycle in the network, as described earlier in section 2.3 on Graph Theory. The phenomenon is characterized by the maximum real eigenvalue of the adjacency matrix representing the system. The rate was found by Borrett *et al*. to be heavily influenced by the number of nodes (size of the adjacency matrix) and the number of direct links (Borrett, Fath et al. 2007). A power law degree distribution, shown in Figure 5(a) (Patten 1985), was found for the pathway proliferation in ecosystems (Borrett, Fath et al. 2007). The power-law degree distribution implies a topology where a few nodes in the system have a large number of connections while most nodes have very few connections (Barabási 2002). Network robustness to random node deletion has been related to this asymmetric structure (Albert, Jeong et al. 2000, Dunne, Williams et al. 2002).

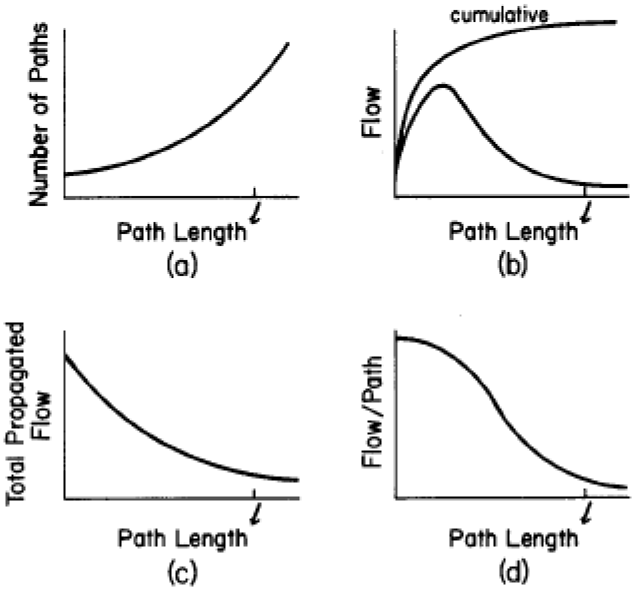


Figure 5: Generalized functions of path length, *l*. (a) number of paths $a_{ij}^{l}$, from one compartment of another. Figure from (Patten 1985).

Pathway proliferation has a strong influence on the development and significance of indirect flows (Borrett, Fath et al. 2007), the importance and probable dominance of which has been investigated for ecosystems (Higashi and Patten 1989). A faster rate of pathway proliferation, or a higher cyclicity, signifies that short indirect pathways are more numerous. Because shorter indirect pathways tend to process larger indirect flows, a higher cyclicity increases the possibility that indirect flows will dominate direct flows (Borrett, Fath et al. 2007). Salas and Borrett tested the probable dominance of indirect effects using 50 empirically based trophic ecosystem models (food webs) (Salas and Borrett 2011).

## 2.4 Industrial Symbiosis and Eco-Industrial Parks

The first fully operational industrial estate (also known as an industrial park, defined as an area zoned for the purpose of development and heavy industry, as opposed to offices and light industry characteristic of a business or office park) in the world was set up in 1896 in England (Dahlman, Katterbach et al. 1992). It wasn't until the 1950's and 60's that growth of industrial estates exploded (in 1940 the US lead the world count with only 33 (Dahlman, Katterbach et al. 1992)), in excess of 12,000 industrial parks and processing zones were documented around the world in 1998 (Cote and Cohen-Rosenthal 1998). This growth, coupled with the standard linear production chain, created a substantial threat to the environment. *"Their [industrial estates] size and number are expanding at a time when the world's remaining natural ecosystems are rapidly shrinking, particularly in countries undergoing fast industrialization"* (1997). Stricter environmental legislations in response to this explosive growth have created an increased demand for cost cutting and efficiency improvements in all sectors (EU 2000, EU 2003). The United Nations General Assembly has declared that 2014-2024 will be the 'Decade for Sustainable Energy for All' (2012).

The field of industrial ecology uses concepts of biological ecology to serve as sustainable organizing principles for modern society. This process highlights and promotes system features which mirror those seen in nature, such as structural properties, flow patterns and performance goals (Erkman 1997). Decades ago, the potential for transferring ecological principles to human systems was recognized as a way to increase the efficient use of energy and resources and reduce waste (Odum 1969). More recently biology has been used as inspiration for everything from sustainable urban systems, termed "infrastructure ecology" (Xu, Weissburg et al. 2012), to cities and sustainability monitoring systems (Bodini 2012).

In 1989 Frosch and Gallopoulos proposed to convert the traditional manufacturing model, one composed of linear industrial chains of activities, to an integrated model they deemed an 'Industrial Ecosystem' (Frosch and Gallopoulos 1989). Such a system would use lessons learned from biology to optimize the use of raw materials and energy while minimizing waste through the redefining of effluents as raw material for neighboring processes. The design of closed-loop manufacturing networks is most popularly based on the basic predator-eats-prey structure of food webs (Chertow 2000, Hardy and Graedel 2002) and the resultant cycling of materials and energy (Graedel and Allenby 1995). Using food webs as a model creates a filter, allowing industrial networks to be simplified and organized to mimic food webs, essentially re-describing the industrial network from a biological point of view (Hess 2010). Analogies like these between ecology and industry have become a primary source of network reorganization solutions. "*The analogy between the industrial ecosystem concept and the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogy"* (Frosch 1992).

Diverse industry profiles and biologically inspired symbioses (when traditionally separate industries engage (Chertow 2000)) are characteristic of the reconfigured bio-inspired networks, which have been shown to reduce environmental burdens and increase efficiencies (Chertow and Lombardi , Jacobsen 2006, van Beers, Corder et al. 2007, Zhu, Lowe et al. 2007, Mayer 2008, Park, Rene et al. 2008, Yang and Feng 2008, Reap 2009). An ideal symbiotic industrial system has been described as one that would be locally closed, recycling everything and producing only services for the use of nearby consumers (Korhonen and Snäkin 2005). There are still many other beneficial characteristics of biological systems beyond this basic interaction that have yet to be exploited by industry designers. Properties that have been proposed as being potentially transferable are stability and resilience or adaptability, believed to be related to diversity and productivity (Mayer 2008, Xu, Weissburg et al. 2012, Fath 2014). These qualities have not been investigated beyond conceptual speculation despite their economic importance. Success requires a solid understanding of ecological systems as not all underlying concepts can be translated item by item (Levine 2003, Mayer 2008). Creating a solid foundation for a model is one of the main goals of this dissertation, only from this step will we be able to define ecosystem-like features and translate and apply biological principles.

### 2.4.1 Eco-Industrial Parks

Industrial estates designed following ecosystem principles are termed ‘eco-industrial parks’ (EIPs) and seek to embody desirable food web properties. A food web’s ability to adapt to internal scarcities and changing environmental conditions is enviable (Korhonen and Snäkin 2005) and their ability to meet all necessary aspects of life allows for the definition of a sustainable system (Keller and Botkin 2008). Taking the theory “form follows function” to be true, by mimicking the structure of ecosystems EIPs may acquire their adaptability along with other beneficial characteristics as well. When multiple firms or facilities achieve higher system efficiency through the exchange of ‘waste’ energy and materials, industrial symbiosis is achieved, named for the analogous mutually beneficial interactions often found between biological species (Erkman 1997, Chertow 2000). An EIP is a sustainable, integrated industrial community of collocated firms in a bounded geographic area, typically an industrial park (McManus and Gibbs 2008). One of the greatest benefits of EIPs is the exchange of materials which would otherwise be sent to a landfill or dumped. This limits the consumption and costs of raw material and the dumping and recycling costs of waste. Other notable environmental benefits of EIPs are reduced resource consumption, costs, and emissions.

One of the most popular EIP examples is the Kalundborg EIP in Denmark. The structure of the exchanges within Kalundborg as of 2010 is shown in Figure 6. The successful EIP has recorded significant raw material, water and energy reductions due to over 30 symbiotic relationships, which have naturally developed over the last 50 years (Hardy 2001, Mitchell 2003, Jacobson 2006). The mutually beneficial relationships within Kalundborg have resulted in the EIPs yearly $CO_2$ emission being reduced by 240,000 tons, water savings of 3 million $m^3$ through recycling and reuse, 30,000 tons of straw being converted to 5.4 million liters of ethanol, 150,000 tons of yeast replacing 70% of the soy protein in traditional feed mix for more than 800,000 pigs, and the recycling of 150,000 tons of gypsum from desulphurization of flue gas ($SO_2$), replacing the import of natural gypsum

($CaSO_4$) (Drake 1990, Jacobson 2006, Layton, Reap et al. 2012). The long history of Kalundborg also provides long term growth data for more in-depth studies, necessary for the study and replication of its sustainable design.

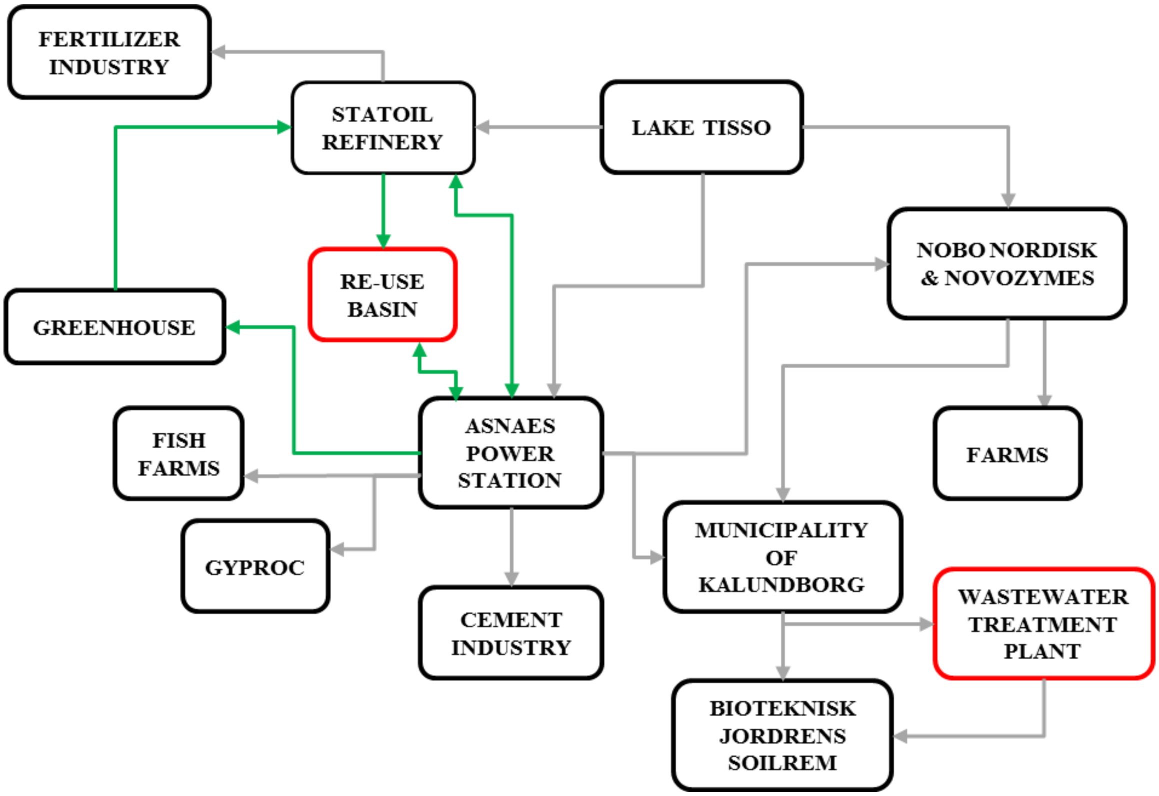


Figure 6: Kalundborg Eco-Industrial Park as of 2010. Cyclic interactions are highlighted in green. Adapted from the Kalundborg website .

The AES Thames Eco-Industrial Park was based on a detailed plan laid out in 1997 suggesting additional biologically inspired relationships between a power plant, a craft brewery, and other industries (Becker, Minick et al. 1997). Unfortunately the power plant declared bankruptcy in 2011 and was bought and dismantled by the end of 2012 (Johnson 2011, Mosher 2013). The proposed eco-industrial park, which linked materials and energy for soil, thermal energy, farm products and packaging materials by adding a brewery and a farm to an existing group of industries, has been widely studied and is often used as an example eco-industrial park (Chertow 2000, Hardy 2001, Chertow, Portlock et al. 2002, Saikku 2006, Daddona 2011).

Clark Special Economic Zone, located in a former American military base in the Philippines, as of 2002 consisted of a proposed integration of solvent recovery, oil processing, tire processing, gray water treatment, composting, and a power plant. The EIP used in analysis here is based on guidance provided by the Yale school of Forestry and Environmental Science in 1998 as to potential symbiotic relationships. It is unclear whether these recommendations are in practice today (Short , 1996, Bennett, Heitkamp et al. 1998, Cote and Cohen-Rosenthal 1998, Chertow, Portlock et al. 2002, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007).

The Green Triangle system is a proposed resource exchange between the Franklin Park Zoo, Arnold Arboretum and other nearby entities (Kellogg, Pfeister et al. 1999, Hardy 2001, Saikku 2006, Gibbs and Deutz 2007).

The Renova Resource Recovery Park in Arecibo, Puerto Rico is a proposed EIP centered on a waste-to-energy facility intended to incinerate municipal waste and provide steam and electricity to the park tenants. The presence of fallow sugarcane fields near the park would allow for the integration of agricultural components and agriculturally based activities, believed to enhance the ecological characteristics of industrial networks (Hardy 2001, Chertow, Portlock et al. 2002, Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007).

A carpet EIP based on a proposed closed loop carpet production, use, reuse, and recycling across 13 counties in metropolitan Atlanta was collected by Reap (Reap 2009). The EIP includes a primary carpet manufacturer as well as several collection and recycling sites that feed material back to the manufacturer and/or to landfill sites.

The Burnside Eco-Industrial Park in Halifax, Nova Scotia is made up of more than 1500 businesses. With support from the Eco-Efficiency Center at Dalhousie University they have all improved their environmental performance (2012). Waste management costs for some firms have been reduced by way of cleaner production techniques as well as reduced discharges to air and sewers and reduced disposal of solid wastes through exchanges (Peck, Callaghan et al.). According to some, Burnside does not meet the requirements of complex resource exchanges in order to be called an EIP (Lam 2007), however according to the Burnside Ecosystem Model provided by Cote in 2009 there are resources exchanges within Burnside which result in a cyclicity value corresponding with the existence of internal cycling (Cote 2009).

The Kwinana EIP is a large and complex industrial symbiosis in Western Australia which is dominated by heavy industries that successfully exchange wastewater, energy and inorganic materials (van Beers, Bossilkov et al. 2005, Corder 2008).

The Uimaharju eco-industrial park began as a sawmill in the 1950s. In time, other businesses moved into the region and began using the outputs, byproducts and wastes generated by already established activities. In the most recent configuration, a sawmill, a pulp mill, and a combined heat and power plant form the core of an industrial cluster that also includes waste water treatment, gas recovery and ash treatment (Korhonen and Snäkin 2005, Reap 2009).

Pomacle-Bazancourt is described as both an industrial ecosystem and a research and development ecosystem, with materials and energy exchanges as well as a collaborative R&D center between the three main shareholders: the Chamtor wheat refinery, the Cristal Union sugar beet refinery, and the Cristanol ethanol plant. Steam, wastewater treatment, and combined heat and power from a biomass plant supplies Chamtor, Cristal Union, and Cristanol as well as the research center and Soliance Cosmetic, the later avoids 100,000 tons of $CO_2$ emissions and avoids the use of fossil fuels for energy (Chauvet 2012). Sources for the ethanol production at Cristanol come from the wheat and sugar beet refineries. Groundwater and energy savings are also obtained through the use of 50,000 $m^3$ of water from sugar production at Cristal Union by Chamtor (Chauvet 2012).

Ulsan Industrial Park in Korea is another EIP success story. The EIP is part of a 15-year project for cleaner production infrastructure in Korea, motivated by their almost complete dependence on imported natural resources and high air pollution rates (Park and Won 2007, Park, Rene et al. 2008). In 2005 Ulsan contained synergies between approximately 40 companies, a few of the larger and more economically successful synergistic relationships are outlined in Table 1 (Park, Rene et al. 2008). In 2007 there were 70 symbiotic activities within the park, including collective utility systems, by-product exchanges, shared steam energy and excess steam, and industrial water recycling (Park and Won 2007). In 2008, it was predicted that 56 new synergistic projects would be completed by 2010, and if the 5 major companies in Ulsan participated, approximately 35 million US dollars per year would be saved (Park, Rene et al. 2008).

Table 1: Industrial symbiotic relationships in Ulsan EIP as of 2004 (Park, Rene et al. 2008)

| **Material** | **From** | **To** | **Sold/ free** | **Investment (US $10,000)** | **Annual Revenue (US $10,000)** |
|---|---|---|---|---|---|
| Pure water | SK Corp. | Koentec | | - | - |
| Steam | Koentec | SK Corp. | Sold | 209 | 411 |
| Steam | SK Corp. | Ulsan Pacific, Taeyoung Ind Corp | | - | - |
| Zn recovery | LS-Nikko | Koreazinc | Sold | - | 461 |
| Cu recovery | Koreazinc | LS-Nikko | Sold | - | 1739 |
| Steam | LS-Nikko | Hankuk Paper | Sold | 696 | 300 |
| Biogas | Y-WWT | SK Chemical | Sold | - | 26 |
| Waste MeOH | Samsung | O-WWT | Free | - | 130 |

Connecticut Newsprint sends sludge, which would otherwise be disposed of, to three different industries. This sludge does not however re-enter the system as a resource after processing. It is the processing of waste followed by its reintroduction as a raw material that is the fundamental process of a food web, allowing for the highly efficient use of material and energy. The other industrial networks in this third grouping all share this characteristic.

Gladstone in 2005 exchanged fly ash, treated effluent, caustic soda, solvents and used tires (Corder 2005). The proposed system of exchanges in 2008 incorporated 9 additional industrial and 19 additional links, creating an impressive looking structure which looks highly cyclical (Corder 2008).

Unfortunately the presence of symbiotic relationships alone does not guarantee success, as there are also many EIP failures. The world of production and development is constantly fluctuating however and can be difficult to predict in the long term. Monetary problems halt the implementation of many exciting EIP plans, companies which must fill such plans may remain unconvinced that moving locations would be financially beneficial, or things may fall apart for any number of reasons between early development and maturation. Intentionally planning, designing or managing a functioning EIP is very difficult (Korhonen and Snäkin 2005). Gibbs and Deutz showed the difficulty of creating a "planned 'Kalundborg'" after conducting more than 60 interviews across 16 different EIPs (Gibbs and Deutz 2007), ten years after it was hypothesized that evolution of relationships at Kalundborg may not be an easily transferable pattern (Ehrenfeld and Gertler 1997). The symbioses at Kalundborg were created through a "sequence of independent, economically driven actions (Ehrenfeld and Gertler 1997)" very different than the ground-up strategic mapping of the EIPs which followed. Heeres *et al.* cites the lack of success with EIP development (beyond those barriers which are universal to any venture: risk, finance, mobility of capital, or elsewhere located higher pay-back options (Chertow 2000)) to be that most focus on developing physical exchanges (energy, water, material, waste) (Heeres, Vermeulen et al. 2004). Rather, low risk successes may lead companies to participate in higher risk EIP developments, as seen in the Netherlands. Connections between companies there are initially created through low risk pollution prevention programs related to utility sharing (wastewater treatment or combined heat and power), after which more dependent relationships are formed.

### 2.4.2 Previous Studies of Eco-Industrial Parks

The benefits of the food web-like structure for EIPs has been extensively documented, e.g. (Ehrenfeld and Gertler 1997, Chertow 2000, Chertow and Lombardi 2005, Jacobsen 2006, van Beers, Corder et al. 2007, Zhu, Lowe et al. 2007, Park, Rene et al. 2008, Yang and Feng 2008, Reap 2009, ZERI 2012, Fath), showing that the exchanges characteristic to this structure contribute to an overall reduction of environmental burdens due to energy and material consumption. For example, a carpet recycling network designed to mimic food webs was found to positively correlate ($R^2$ = 0.96 in Figure 7) with standard cost- and emissions-minimizing designs using a unique structural configuration, which could provide inherent network robustness and stability (not considered by conventional industry optimization models)  (Reap 2009). Chertow and Lombardi present clear evidence of the substantial environmental and economic benefits that result from the symbiotic relationships characteristic of biology (Chertow and Lombardi). Guayama in Puerto Rico is home to an EIP that has seen a 99.5% reduction in SO2 emissions and a savings of 4 million gallons of freshwater per day (Chertow and Lombardi). The literature indicates that these benefits can occur on an absolute basis as well as a relative basis (per unit of production). Therefore one can argue that formation of these systems generally leads to environmental improvements.

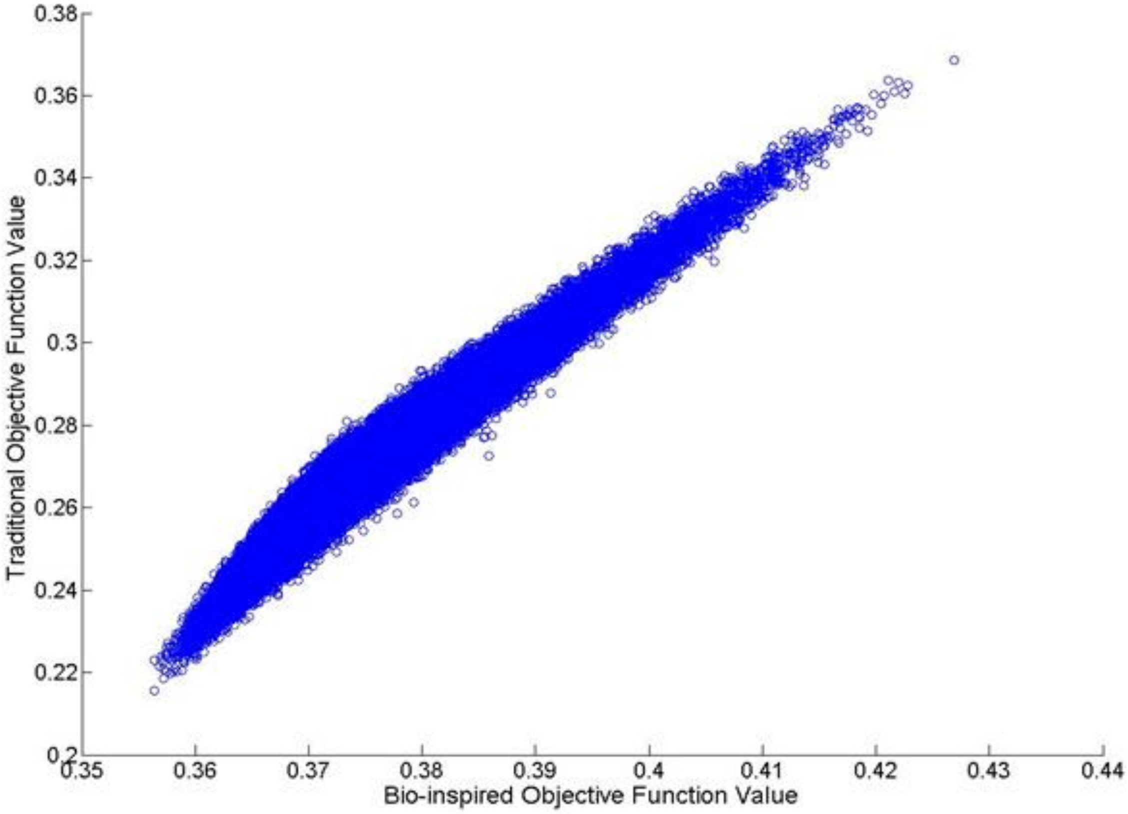


Figure 7: Traditional vs. Bio-Inspired Objective Function Values for 100,000 Randomly Generated Carpet Tile Recycling Network Designs. *Figure from* (Reap 2009).

Mayer outlines one approach for a food web analysis of a Forest Industry but does not complete the analysis (Mayer 2008). The approach consists of three steps: (1) identifying the boundaries of the system, (2) identifying the regimes that are sustainable, defined as being both desirable and stable, and (3) identifying disturbances that can push the system out of the defined sustainable regime. A sustainable regime is described as one that is profitable, has a diversity of firms supplying inputs and producing outputs, provides social and economic support for the local economy, and can satisfy supply and service rates over a specified time period. Examples of system disturbances are large demand fluctuations, feedstock disruptions, and financing problems. The importance of clearly identifying the system boundaries for an ecological analysis of EIPs is reiterated by a number of IE researchers e.g. (Korhonen and Snäkin 2005).

A system called *MatchMaker!* was attempted in 1997 that collected together material flow information for a range of companies for the benefit of those wanting to form EIPs. Insufficient information was available at the time to fully implement the project unfortunately (Brown, Gross et al. 1997). At the time of this dissertation no further work had been published regarding this lofty project.

Newly implemented by-product exchange networks and newly discovered naturally occurring symbiotic relationships are increasing the size and power of the available dataset e.g. (Cote and Cohen-Rosenthal 1998, Chertow 2000, Hardy 2001, Lowe 2001, Chertow, Portlock et al. 2002, Hardy and Graedel 2002, Mitchell 2003, Rotkin, Lubeck et al. 2004, Korhonen and Snäkin 2005, Saikku 2006, Chertow 2007, Gibbs and Deutz 2007, Reap 2009, Mathews and Tan 2011, 2012) and proving that these relationships are more prevalent than first thought (Chertow 2007, van Berkel 2009). Despite the acknowledged connection between industrial symbioses and ecosystems, surprisingly few studies rigorously investigate this link. The literature contains anything from brief profiles to extensive summaries for existing and planned EIPs, almost all however are without an ecological analysis (1996, Mitchell 2003, Rotkin, Lubeck et al. 2004, Saikku 2006, Mathews and Tan 2011, ZERI 2012). Gibbs and Deutz completed an internet survey of 35 American EIPs and 26 European EIPs, following up on 19 of them (14 operational and 5 planned) by email, fax, and phone calls (Gibbs and Deutz 2007). Sixteen EIPs were chosen for their review based on symbioses and local and social objectives. Côté and Cohen-Rosenthal created a collection of 15 American EIPs and 9 potential Canadian EIPs for their review on the design process of EIPs (Cote and Cohen-Rosenthal 1998). Mathews and Tan compare 5 Chinese EIPs to 4 well documented international EIPs (Mathews and Tan 2011). Mitchell has a collection of 9 summary profiles of existing and planned EIPs (Mitchell 2003). Rotkin provides brief summaries of 18 EIPs however similar to Mitchell there is no flow information included

(Rotkin, Lubeck et al. 2004). Saikku provides an extensive listing of 35 American EIPs and 25 European EIPs both planned an operational however only 8 of the 60 have flow information included (Saikku 2006). The Zero Emissions Reach and Initiatives Foundation (ZERI) provides information on two EIPs and flow information for a third (ZERI 2012). The Yale Forestry and Environmental Science Bulletin has more detailed papers covering seven different EIPs (Becker, Minick et al. 1997, Bennett, Heitkamp et al. 1998, Morton, Simon et al. 1998, Abuyuan, Hawken et al. 1999, Johnson, Stewart et al. 1999, Kellogg, Pfeister et al. 1999, Hardy, Hedges et al. 2000). These collections all have significant overlap in the EIPs they cover and almost none of them are there ecological analyses included.

When an ecological analysis is included, studies of EIPs in the literature tend to focus on a few ecological components, mainly the food web metric *connectance* (outlined later in section 3.3.2). Van Berkel has looked at the characterization and quantification of connectedness (or symbiotic intensity) and the quantity of symbiotic resources flows in four well known ‘successful’ EIPs (van Berkel 2009). The food web properties *throughput* and *roundput* were studied in comparing the linear movement of materials and energy in industrial networks to the cyclical flow in ecosystems (Korhonen and Snäkin 2005). There have been a few research groups that have developed different ranking systems for EIPs according to the development stage. Korhonen and Snäkin created a 3 type ranking which ranges from immature/newborn systems (type I) to mature-adult systems (type III) (Korhonen and Snäkin 2005). Chertow suggests a 5 type system based on the type of material exchanges taking place in the system (Chertow 2000). A Type 1 industrial system is based on waste exchanges, the recycling and reuse of recovered materials at end-of-life stages, which are typically one-way (Chertow 2000). The exchanges in a Type 2 industrial system are concentrated within a single facility or firm (Chertow 2000). Types 3, 4, and 5 are EIPs in the traditional sense in that the exchanges are between firms which are respectively colocated, not colocated, and virtually connected (Chertow 2000). McManus and Gibbs (McManus and Gibbs 2008) propose three different classifications for EIPs based on the synergies and locations between the interacting companies. Within the umbrella EIP the pair suggests ‘Green Industry Park’ for those EIPs that are composed of ‘green’ industries but the industries have no synergistic connections. ‘Integrated Eco-Industry Parks’ for those EIPs with syneriges bewteen the companies and where the companies are georgraphically concentrated and ‘Networked Eco-Industrial System’ when the companies span a larger georgraphical area (metropolitan or larger). The Yale School of Forestry and Environmental Studies from 1997 to 1999 examined 18 potential EIPs (Becker, Minick et al. 1997, Brown, Gross et al. 1997, Bennett, Heitkamp et al. 1998, Morton, Simon et al. 1998, Abuyuan, Hawken et al. 1999, Johnson, Stewart et al. 1999, Kellogg, Pfeister et al. 1999). These studies focused on possible flows that could be exchanged within the park and concepts from industrial ecology. These studies, and many others focusing on EIPs lack any real data and or food web metric analysis e.g. (Heeres, Vermeulen et al. 2004).

#### 2.4.2.1 Ecosystem Network Analysis Applied to Eco-Industrial Parks

Quantitative ecological analyses of EIPs focus on the translation and comparison of structural food web metrics. Hardy and Graedel analyzed 18 hypothetical and realized EIPs using the ecological metric connectance (Hardy and Graedel 2002). In food web analysis, connectance is a measure of the number of interactions which are active in a community as compared to all possible interactions (see equations 11, 12, and 13). Comparing the EIPs to a set of food webs collected by Briand (Briand 1983), they showed that industrial systems with symbiotic, or “ecosystem-like,” relationships displayed similar mean values for connectance. Although this analysis was significant in pioneering the use of ecological metrics to analyze EIPs, it illustrates some difficulties in applying ecological methods to human industrial systems.

Food web ecologists have not always been clear about the assumptions and motivations of their analyses, particularly prior to the early 1990’s (Martinez 1991, Polis 1991, Cohen, Beaver et al. 1993). As such, difficulties in the application of food web analysis methods to industrial networks commonly occur (Graedel 1996, Hardy and Graedel 2002, van Berkel 2009, Wright, Cote et al. 2009, Dai). The first major difficulty is in identifying the appropriate food web calculations for the structure of industrial networks, which are similar but not identical to that of food webs. For example, parameters describing linkage patterns in food webs are calculated differently depending on the types of interactions that are represented in the graphical/structural representation (web) of the community. Hardy and Graedel (Hardy and Graedel 2002) use an equation that is not appropriate for understanding the input-output structure of food webs (see section 3.3.2 following), making it difficult to benchmark EIPs relative to their food web analogs. This issue can be seen frequently in the literature (Graedel 1996, Hardy and Graedel 2002, van Berkel 2009, Wright, Cote et al. 2009, Dai), suggesting a need to more carefully define appropriate parameters and conditions under which various types of analysis may be used. The second major issue is comparing EIP results to food web datasets that may not accurately represent real biological communities. The rapid rise in the extent and importance of food web analysis in the early 1990's sparked a major effort among ecologists to assess the quality of existing data and suggest appropriate data collection methods (Polis 1991, Cohen, Beaver et al. 1993). These works document major inconsistences in data collection methods and potentially significant biases in the analytical results of ecosystems collected up to then. Greater emphasis has been placed upon the quality of food web data since these two important papers.

A quantitative comparison of a simple linear industrial network, nonlinear industrial networks, and naturally occurring food webs using structural metrics from ecology *(Hardy 2001)* reveals that: (1) the structures of existing symbioses and food webs differ statistically; (2) symbioses structurally fall between linear flow systems and food webs (Reap 2009). Findings like these highlight the need to better apply available biological knowledge in resource network design and for " *the appropriateness of transplanted ideas [to] be rigorously investigated"* (Mayer 2008). This sentiment is echoed by others in the field (Erkman 2003, Isenmann 2003, Ayres 2004, McManus and Gibbs 2008) who outline major differences between the two network types that without more work are felt to be preventative to the forward movement of a working analogy. Ayres (Ayres 2004) argues that there are four major differences between ecology and industry: 1) the lack of primary producers in industrial networks, 2) industrial networks produce goods and services while ecosystems produces essentially "more of itself" as waste only, 3) market and voluntary exchanges driving industry are lacking in ecosystems, and 4) evolution in each of the two systems has different drivers, reproductive success or genetic mutations drive biological evolution and 'intelligent economic agents' drive industry evolution. These differences are felt by some to be preventative to the modeling of EIPs after food webs (Tudor, Adam et al. 2007, McManus and Gibbs 2008). Other work however argues the reverse, that nature is structured by the efficiencies of open competition much like a free market economy (Tilman 2000). A successful model created through a fundamental understanding of why emulation of biological network patterns leads to environmentally superior industrial resource networks would create a bridge between observations and theory that can lead to concrete design guidelines (Chorley and Haggett 1967). Answering this question is the other overarching objective of this work.

## 2.5 Summary of Literature and Conclusions

Industrial ecology has evolved from the problem of dematerialization and what is known as "end of pipe" syndrome. These issues, coupled with limited resources and a changing climate, have resulted in the necessity for considering ultimate waste and disposal within the design process. The creation and study of eco-industrial parks follows the design principle *form follows function*: by mimicking the structure of ecosystems, which have evolved to thrive in non-ideal and fluctuating conditions, EIPs may acquire their adaptability along with many other beneficial characteristics. A thorough review of the literature has shown however that a better understanding of biological ecosystems is greatly needed in order to find and apply key components from ecosystems to industry.

Understanding structure and function allows for the anticipation of the behavior of a system, a very useful skill for both natural and man-made systems and the subject of much work in ecology. The literature has shown that applying ecological principles to industry and engineering requires that important structural components such as species be defined in industrial analyses in a way that is functionally equivalent to its use in natural ecology. The many structural aspects of ecosystems have not been well understood by EIP designers, presents a problem for industrial ecology as this is the basis for the model. For example the translation of species to an industrial network is not a straightforward one as there is not an easy analogy for genetic relatedness or at least, not one that has been proposed. Creating a solid foundation for a model is one of the main goals of this dissertation; only from there will ecosystem features be defined and translated to industry allowing ecosystem principles to be applied.

Food web literature has shown that a significantly greater emphasis has been placed upon the quality of food web data since the early 1990's, a change found here to be significant enough to warrant a guideline that only those food webs collected after this point be used in comparisons with EIPs. The major conclusion from the early 1990's was that actual food webs are significantly more complex than those that had been published up to that point. Characteristics such as omnivory, cannibalism, and structural looping were all found to commonly exist whereas prior they had been ignored as unreasonable. The diversity of species represented in the food webs prior to the early 1990's was found to be an inaccurate depiction and provided an "oversimplified caricature" of real biological communities. The careful review of the ecological literature collected in this dissertation significantly aids in the success of EIP development and is something that was found to be lacking in the EIP literature. Literature reviews on ecosystem collection techniques and analyses provide an in-depth knowledge of the biological structures that EIPs are designed to mimic, helping to create a better analogy between food webs and EIPs. This insight is especially important as one of the most cited ecological analysis of EIPs up to this point, one by Cohen and Briand (Briand and Cohen 1987), used a food web dataset that was found from the literature reviews done here to be largely deceiving, called out by one major paper as being composed of “depauperate webs” (Pimm, Lawton et al. 1991).

The literature on EIPs revealed that a large and comprehensive dataset of EIPs is an immediate need in the field for any sort of progress to be made. This lack of real industry data imparted limitations on the types of food web analyses that were able to be done and the conclusions that could be drawn when they were done. The analyses applying food web metrics to EIPs that were found in the previous literature tended to focus exclusively on the metric connectance, representing the ratio of existing connections to the total possible connections in the system. The thorough literature review done on food webs and ecologists’ analyses thereof has shown that the metric is highly dependent on the size of the network, making it ill-suited for a direct comparison between the biological and industry networks. Other potentially desirable properties of food webs, such as stability and resilience which are believed to be related to diversity and productivity, have not been investigated beyond conceptual speculation in EIPs. Huge strides will be made in the field of EIP development with a better understanding of the study of food webs. These findings are covered in depth in chapter 3.

# CHAPTER 3

# NATURAL FOOD WEBS VS. INDUSTRIAL SYSTEMS: COMMONALITIES AND DIFFERENCES

## 3.1 Research Questions to be Addressed

Despite leading to reductions for environmental impacts and burdens, eco-industrial parks (EIPs) fall short of their biological inspiration. Doubt began circulating in 2004 on whether industrial ecology would ever move beyond theory and speculation, i.e. ‘what could be done’ (Levine 2003, Ehrenfeld 2004, Eilering and Vermeulen 2004, Gibbs and Deutz 2007). The field of industrial ecology has been questioned if it can move from “the descriptive analysis of materials and energy flows in industrial systems toward a prescriptive framework offering concrete solutions and practical measures for policy makers and business managers (Korhonen, von Malmborg et al. 2004).” This chapter addresses how bio-inspired patterns, principles and metrics can be best used for industrial resource network design. If a useful ecological analysis of eco-industrial parks is desired, this chapter lays out the do’s and do not’s. Understanding the commonalities and differences between natural food webs and eco-industrial parks coupled with a detailed analysis of the current literature on EIPs shows the best and worst practices in applying an ecological analogy. This understanding of food webs from an ecological perspective as well as the state of the current analogy with industry is especially important as in previous work analogous industry definitions for food web terms and concepts are unclear and non-uniform. The research goal to establish industry analogous definitions and usages for basic ecological quantities species, functional groups, linkages, and matrix definition are addressed.

## 3.2 Food Web Terminology and Industry Definitions

The importance of characterizing the anatomy of ecological networks is given by Strogatz: “structure always affects function” (Strogatz 2001). By mimicking the structure of these biological networks, the hope is that the functioning of human systems will mimic the inherently sustainable natural world as well. The appropriate application of ecological principles and analyses depends on building models that specify how principles from biology are translated to industry, and back again. One biological model for ecosystems is a food web. Somewhere during the process of translating this model to industry the defining characteristic of an ecosystem (the web-like structure) is dropped and industry is left with a unidirectional, top-down ‘food chain’ (Graedel 1996). Companies within an industrial park or components in an industrial cycle are cast as species, and the material and energy exchanges between them are analogous to the transfer of caloric energy which supports the species (metabolism). At first glance the comparison may seem a complete one, however the transfer of ecological properties and principles to industry is highly complex and much is missing. Definitions have led to the sustainable design slogan “waste equals food,” a slogan that is not consistent with systems in nature and does not fully capture the important workings of ecological systems. The lack of a well-translated framework has led to many discrepancies in the implementation and interpretation of ecological principles and how they advise the organization of industrial system (Hess 2010). A framework built on real and complete ecological knowledge is of the utmost importance to accomplish this goal. Extensive literature exists to aid in the successful translation of many desirable properties found in nature to industry e.g. (Odum 1969, Cohen 1982, Pimm 1982, Pimm 2002).

### 3.2.1 Analogous Industry Definitions

Many important aspects of food webs have not yet been translated to industry. Some aspects have been purposefully ignored due to a lack of understanding with regards to how to apply the properties to an industrial setting e.g. (Graedel 1996). Table 2 outlines ten prominent components of food webs comparing the ecological usage to the industrial usage, or in some cases lack of use in industry.

Table 2: Industry definitions for ecological terms and available references for defining the ecological terms.

| **Concept** | **Environmental Ecology** | **Industrial Ecology** | **Ecosystem References** |
|---|---|---|---|
| *Species* | Multiple definitions. A group of organisms with the same requirements or possess similar anatomical characteristics and have the ability to interbreed. | A company distinct from other companies; each company is assumed to have different requirements. | (Wilson 1999, Loreau 2000, Tilman 2000, Williams and Martinez 2000, Collman 2001, Townsend, Begon et al. 2008, Borrett 2013) |
| *Niche* | The set of resources and conditions required by the organism or the role of the organism in the community. | Implicit; each company is a species, suggesting each has a different niche. | (Cohen 1978, Wiens 1989, Cohen and Palka 1990, Leibold 1995, Wilson 1999, Tilman 2000, Williams and Martinez 2000, Woodward and Hildrew 2002, Halnes, Fath et al. 2007, Saavedra, Reed-Tsochas et al. 2009) |
| *Functional Group* | A group of species that have some similar properties and thus share some common roles or requirements, for instance, ground nesting birds. | Not explicitly considered. | (Vinogradov and Shushkina 1978, Gitay and Noble 1997, Wilson 1999, Hooper, Solan et al. 2002, Garmestani, Allen et al. 2006) |
| *Omnivores* | An organism that consumes both plants and animals as primary food; very important to the health and structure of food webs. | Recognized as existent but not explicitly considered (Graedel 1996). | (Fagan 1997, Closs, Balcombe et al. 1999, Williams and Martinez 2000, Neutel, Heesterbeek et al. 2007, Rudolf 2007, Ispolatov and Doebeli 2011, Gellner and McCann 2012, Kratina, LeCraw et al. 2012) |

Table 2 continued: Industry definitions for ecological terms and available references for defining the ecological terms.

| | | | |
|---|---|---|---|
| *Cannibalism* | Consumption of a resource that has been classified to be of the same species as the consumer. | Not explicitly considered. | (Williams and Martinez 2000, Persson, Roos et al. 2003, Rudolf 2007) |
| *Mutualism* | A cooperative interaction benefiting both parties. Commonly in the form of an exchange of services rather energy fluxes. | Recognized as relevant but not explicitly considered (Levine 2003). | (Bascompte, Jordano et al. 2003, Bascompte and Jordano 2007, Thebault and Fontaine 2008, Bascompte 2009, Bastolla, Fortuna et al. 2009, Ings, Montoya et al. 2009, Holland, Wang et al. 2013) |
| *Trophic Structure* | Described by a circuitous food web structure having no 'top predator' and where materials and energy may travel in different circuits. | Top-down food 'chain' with a roughly linear organization and unidirectional material/energy flow. | (Vinogradov and Shushkina 1978, Strong 1992, Hairston 1993, Martinez and Lawton 1995, Christian and Luczkovich 1999, Jordan and Molnar 1999, Williams and Martinez 2000, Camacho, Guimera et al. 2002, Rudolf 2007, Joppa, Bascompte et al. 2009) |
| *Topography* | Multidirectional links between species; large differences among species in the number of links; hierarchical or nested organization is common. | Limited and unidirectional links between 'species'; little higher level structuring. | (Martinez and Lawton 1995, Dunne, Williams et al. 2002, Heymans, Ulanowicz et al. 2002, Teng and McCann 2004, Fath 2007) |
| *Recyclers/ Detritivores* | A trophic species that is crucial to the circulation and efficient usage of material and energy in a food web. | Undervalued and misunderstood. | (Patten 1985, Allesina, Bodini et al. 2005, Borrett, Fath et al. 2007, Fath, Scharler et al. 2007, Halnes, Fath et al. 2007) |
| *Indirect Effects* | Occur when one species affects another through a "shared contact" species. | Not explicitly considered. | (Patten 1985, Strauss 1991, Wootton 1994, Heymans, Ulanowicz et al. 2002, Rudolf 2007, Schmitz 2009, Salas and Borrett 2011, Borrett 2013, Holland, Wang et al. 2013) |

Table 2 continued: Industry definitions for ecological terms and available references for defining the ecological terms.

| | | | |
|---|---|---|---|
| *Interaction Strength* | Also known as "link weight," a strong or weak interaction can vary depending on the measurement chosen and the type of linkages being documented. | Not explicitly considered. | (de Ruiter, Neutel et al. 1995, Laska and Wootton 1998, Closs, Balcombe et al. 1999, Berlow, Neutel et al. 2004, Neutel, Heesterbeek et al. 2007) |

### 3.2.2 Industry Desirable Food Web Properties

Models and structural metrics have been developed to analyze and explain specific properties of ecosystems, such as the system's ability as a whole to withstand environmental fluctuations and support exclusive species, which could be immensely beneficial to industry (Schoener 1989, Pimm, Lawton et al. 1991). Findings that food webs are composed of strongly connected compartments, with weak interactions between the compartments, a modular structure that is hypothesized to increase the overall systems stability by localizing interactions and disruptions (May 1973, Pimm 1979, Borrett, Fath et al. 2007), however this hypothesis has been difficult to fully resolve (Cohen, Beaver et al. 1993, Polis and Strong 1996). Ecosystem robustness and stability could lend themselves to easing the damage caused by supply chain disruptions, which reduce the share price of the affected companies so significantly that 80% of companies worldwide consider better protection of supply chains top priority *(Bhatia, Lane et al. 2013)*.

In 1969, Odum recognized that ecological systems, particularly mature ones, are associated with a high degree of internal recycling of energy and materials, such that the amount of new inputs into the system is small compared to what is transformed among the system components (Odum 1969). Human systems in contrast (e.g. agricultural ones) are geared for production rather than efficiency, resembling young rather than mature natural systems. Odum has suggested mimicking mature systems would help shift the focus of human systems from production to efficiency (Odum 1969). One desirable property of mature systems is a complex food-web structure; a proliferation of connections between species that exchange material and energy (Fath 2007). The centripetal nature of food web structure is also a selling point for industry. When a species becomes more efficient in use or acquisition of a resource its population increases. Centripetality results in this singularly focused positive change being cascaded through the system, such that all the populations of species involved are benefited (Ulanowicz 1997, Borrett, Fath et al. 2007). Translated to industry this would mean that a change which benefits one company within an EIP translates into a park-wide positive net effect.

A hypothesis within industrial ecology is that diversity, in the sense that a wide range of species types are contained within any system, could contribute to a more stable system: when one firm departs the system may adapt or recover by another actor(s) stepping in to fulfil the supplying role (Korhonen and Snäkin 2005).

An analysis of 40 food webs by Briand indicates that connectance, which is a measure of the number of direct to the total possible interactions in a web and an important parameter in the previous ecosystem analyses, declines as variability of the environment increases (Briand 1983). Following a line of reasoning strongly influenced by May’s theoretical analysis (May 1972), Briand argues that differences in connectance values for ecosystems in stable and unstable environments are the result of limitations in feeding periods caused by environmental fluctuations, which can lead organisms to depend upon intermittent, intense feedings. This suggests a structure which is dependent on the stability of resources, a property of interest for industries.

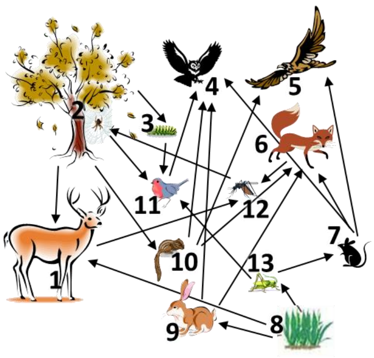
## 3.3 Methods: Structural Food Web Analyses

### 3.3.1 Structural Matrices

Ecologists use simple un-weighted digraphs from graph theory to quantify the characteristics of food web, where every link has a direction and simple implies that there is no more than one link from one to node to any other (Borrett, Fath et al. 2007). Species or functional groups are represented in the digraphs such that any species with identical predators and prey are grouped as trophic species, which has been found to reduce methodological bias in the data (Yodzis 1982, Cohen, Briand et al. 1990, Pimm, Lawton et al. 1991, Borrett, Fath et al. 2007). Many of the characteristics of food webs found may also be desirable from an industrial/economic perspective, and could positively influence things such as cost, emissions, and efficiency (Reap 2009, Layton, Reap et al. 2012). The meaning and calculation of each ecological measure/metric is best understood within the context of an organizational matrix. Organizational matrices are used by ecologists to collect and document the exchanges between species or functional groups within the community at hand. These matrices may document anywhere from predator-prey exchanges to all interactions in a community, including any competition interactions. They may also include cannibalism interactions if the author wishes. For the purpose of our work we will be assuming that cannibalism is present in our industrial systems and use biological systems for which cannibalism has been included.

#### 3.3.1.1 Food Web Matrix [**F**]

One organization matrix for food webs is the food web matrix [**F**]. Analogous to a connectivity matrix (Fath and Halnes 2007), a food web matrix is concerned only with the structural information (links and nodes) of a network and defines the pathways that exist by which material and energy flows from one compartment to another. It is blind to information such as flow rate, quality, and the type of working fluid. A link exists as long as some physical quantity directly joins two nodes. Only flow existence and direction are captured. A food web matrix [**F**] captures the *observed* predator-prey interactions. The left half of Figure 8 depicts a hypothetical food web represented as a directional digraph; the right half represents the web as a food web matrix [**F**]. Since a species (*N*) can be both predator and prey the result is a square matrix. Each row in a food web matrix captures the flow of resources from one species to all species in a web and each column captures the input of resources to a particular species from all species in the web. 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 $(N)*(N-1)$ assuming a given species does not eat itself, and ($N^2$) if cannibalism is allowed (noted as a 1 on the diagonal).



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

Figure 8: Left – A food web of a hypothetical ecosystem with species numbered. Right – A food web matrix where $f_{ij} = 1$ represents a unidirectional link between prey (*i*) and predator (*j*) and a zero represents no link. The matrix documents 13 trophic species and 22 links.

### 3.3.1.2 <u>Community Matrix [**C**]</u>

Ecologists also can express material and energy flows using a community matrix [**C**], which is derived from the food web matrix [**F**]. A community matrix contains *all connections* in a food web, documenting each observed interaction as a bidirectional (non-directional) connection: if predator-*j* feeds upon prey-*i* then the link is documented in the community matrix as $c_{ij} = 1$ and $c_{ji} = 1$. The community matrix also may include interactions such as competition, when two predators feed upon the same prey. For instance, if predator-*k* also feeds upon prey-*i*, then the competition interaction between predator-*j* and predator-*k* would be documented in the community matrix as $c_{jk} = 1$ and $c_{kj} = 1$. This would also describe a situation where *j* and *k* utilize the same non-food resource, if one of these species parasitizes the other, or if they are engaged in a reciprocally positive relationship (mutualism).

The types of interactions represented by the organizing matrix (food web or community) have a strong impact on the magnitude of the parameters derived from it. It is critical to define the most appropriate matrix for the comparison of EIPs to food webs. Obviously, because [**C**] represents the matrix of a non-directional digraph, it will have at least twice the number of links as the corresponding food web matrix [**F**], even if only predator-prey interactions are represented (e.g. each link between *i* and *j* is counted twice). Moreover, [**C**] often times include other interactions, as described above. A community matrix [**C**] is often used by ecologists (Briand 1983) as a representation of the upper and lower bounds of connectance, equations 12 and 13, as opposed to a strict representation of material and energy flows in the food web matrix [**F**]. Figure 2-Left, represents a "lower bound" of existing interactions as it shows only predator-prey interactions. For ease of reference we will refer to this matrix as [$\mathbf{C_L}$] throughout this paper. A community matrix may also include competition, mutualistic, or parasitic interactions in addition to predator-prey interactions. Non-food based interactions are hard to define, and so an upper estimate of the interactions which may be well-defined includes only those food based competition interactions. For ease of reference this will henceforth be referred to as [$\mathbf{C_U}$]. This has created some confusion, as previous industrial network studies have compared results of food web analyses derived from **[C]** to EIPs represented by **[F]** (e.g. (Hardy and Graedel 2002, Dai)). Given that a major goal of eco-industrial parks is to establish efficient material and energy transfer, one logically would express the relationships in an EIP as a biological food web **[F]**.These flows are directionally specific and interactions beyond material and energy flows are not represented.  Therefore we take **[F]** as the appropriate matrix form for food webs as well.

$$\mathbf{C}_l = \text{prey}\quad \begin{array}{r|ccccccccccccc|} & \multicolumn{13}{c}{\text{predators}} \\ & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\ \hline 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 5 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 7 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 9 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 10 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 11 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 12 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 13 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ \hline \end{array}$$

$$\mathbf{C}_u = \text{prey}\quad \begin{array}{r|ccccccccccccc|} & \multicolumn{13}{c}{\text{predators}} \\ & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\ \hline 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 3 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 5 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 7 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 9 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 10 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 11 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 12 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 13 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ \hline \end{array}$$

Figure 9: Community matrices for a hypothetical food web. $c_{ij} = 1$ represents an interaction between species *i* and *j* and a zero represents no interaction. Left- A lower bound for the community interactions in the ecosystem [$\mathbf{C_L}$]. The matrix documents 44 links. Right – A higher well defined estimate for the community interactions in the ecosystem [$\mathbf{C_U}$]. The matrix documents 68 links.

For example in the 2002 analysis done by Hardy and Graedel the pair uses the food web matrix form [**F**] to organize their 18 EIPs. From these food webs the pair calculated the lower bound connectance values from equation 13 for the EIPs and compared these to food web connectance values from equation 12 as calculated by Briand from the [$\mathbf{C_U}$] matrix (Briand 1983). Hardy and Graedel's process summarizes to using the [$\mathbf{C_L}$] matrix from Figure 2-Left being used for the EIP data set and the [$\mathbf{C_U}$] matrix from Figure 2-Right being used for the food web data set. As the interest of the community matrix is all interactions and it is used when one is interested in the stability of all interactions this matrix's use for EIPs is out of place. The aim of the food web matrix however is strictly the depiction of material and energy flows, which is in line with the functions of an industrial network. The authors expect that this was what Hardy and Graedel were implicitly trying to do in their 2002 analysis.

Clearly from here if a food web matrix is used to describe an industrial system it would be desirable to compare biological data from a food web matrix as well.

#### 3.3.1.3 Adjacency Matrix [**A**]

A structural adjacency matrix [**A**] is the transpose of the food web or community matrix. It is used in some metric calculations rather than the previous two matrix forms. Rows represent prey (from) and columns represent predators (to). All other aspects are the same as the previous two matrices.

### 3.3.2 Ecological Metrics: Investigating Structure

The structural measures and metrics used most frequently by ecologists, and which we apply to industrial networks, are defined as follows:

*Species Richness* (*N*) – The total number of unique species in a food web. This is often different from the number of species documented in the ecosystem as species are commonly aggregated. Aggregation into trophic species is widely accepted among ecologists as it has been shown to reduce the methodological biases related to uneven resolution by the observer. It must be noted that ecologists will often refer to their aggregations of species as simply ‘species,’ potentially misleading uninformed readers. Species richness is denoted as ‘*N*’ for nodes, to emphasize that the species from the original ecosystem may have been aggregated. Represented by the size (number of rows or, as the two are equal, columns) of the food web matrix [**F**]. (Briand 1983, Heywood 1995)

*Species Evenness* – A measure of the relative abundances of individuals for each species in the system, qualifies how balanced the community is numerically (Purvis and Hector 2000).

*Species Diversity* – The number and variety of species found in a given region (Heywood 1995). Species evenness and species richness when used together asses the amount of functional variance or diversity in the system as illustrated in Figure 10 (Purvis and Hector 2000). How species is defined has a nontrivial impact on the calculation of these metrics.

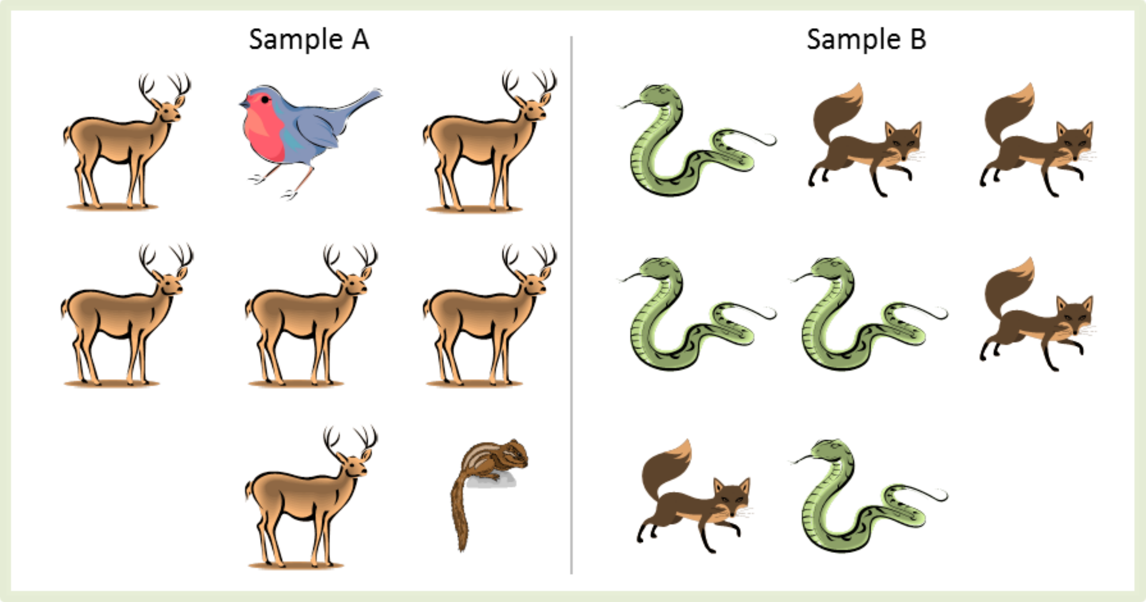


Figure 10: A visual description of the differences between species richness and species evenness. Sample A on the left shows a system which has higher species richness (3 types of species) than Sample B on the right (2 types of species represented) but low species evenness (the butterfly dominates the overall distribution of individuals in the sample). Species evenness shows that the Sample B is balanced as there are the same numbers of individuals of either species. *Adapted from* (Purvis and Hector 2000).

*Number of Links* (L) – The number of direct links between species in a web. Represented by the number of non-zero interactions in the food web matrix [**F**]. As noted, only predator-prey interactions are represented in [**F**], and links are directional. (Briand 1983)

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} \qquad (1)$$

*Linkage Density* ($L_D$) – The ratio of the total number of links to the total number of species in a food web. When linkage density is doubled it gives the average node degree (<*k*>), which is the mean of incoming and outgoing links per species (Dunne, Williams et al. 2002).

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

*Prey* ($n_{prey}$) – Species eaten by at least one other species (Schoener 1989). This is represented by the number of non-zero rows in a food web matrix [**F**].

$$f_{row}(i) = \begin{cases} 1\ for\ \sum_{j=1}^{n} f_{ij} > 0 \\ 0\ for\ \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i) \tag{4}$$

*Predator* ($n_{predator}$) – Species that eat at least one other species (Schoener 1989). This is represented by the number of non-zero columns in a food web matrix [**F**].

$$f_{col}(j) = \begin{cases} 1\ for\ \sum_{i=1}^{m} f_{ij} > 0 \\ 0\ for\ \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{5}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{6}$$

*Prey to Predator Ratio* ($P_R$) – The ratio of the number of species eaten by another species to the number of species that eat another species. This is the number of non-zero rows in a food web matrix [**F**] divided by the number of nonzero columns. The efficiency of use of materials and energy in the ecosystem is partially dependent on this ratio (Bodini and

Bondavalli 2002). If the number of prey (or producers) far exceeds the number of predators (or consumers) the result is an excess of waste produced or unused matter. The opposite scenario, where predator populations exceed prey in the system the system must heavily rely on imports and raw materials into the system. The ratio of prey to predators, or producers to consumers, has not been rigorously investigated in the EIP literature and has the potential for to provide impactful design guidelines.

$$P_R = {}^{n_{prey}}/_{n_{predator}} \tag{7}$$

*Specialized Predator Fraction* ($P_S$) – The fraction of predators that only feed on only one type of species, or are specialized. This is the number of columns in a food web matrix [**F**] that have only one nonzero entry divided by the number of columns in [**F**] with nonzero entries (predators).

$$f_{s-col}(j) = \begin{cases} 1\ for\ \sum_{i=1}^{m} f_{ij} = 1 \\ 0\ for\ \sum_{i=1}^{m} f_{ij} \neq 1 \end{cases} \tag{8}$$

$$n_{S-predator} = \sum_{j=1}^{n} f_{s-col}(j) \tag{9}$$

$$P_S = {}^{n_{S-predator}}/_{n_{predator}} \tag{10}$$

*Connectance* ($c$) – The number of actual direct interactions in a web divided by the total number of possible interactions (the number of species squared), equation 11. If one forbids cannibalism then the number of possible interaction is reduced, and connectance becomes the fraction of nonzero off diagonal elements in the food web matrix [**F**], equation 12 (Yodzis 1980, Briand 1983, Warren 1990). Equations 11 and 12 are for use with directional matrices, where the direction of an interaction is of importance – an exchange from an actor to another. Equation 13 documents all interactions as being of a bidirectional nature; the relationship is between consumer and producer as well as between producer and consumer. This results in twice the number of linkages documented in the matrix representation.

$$c = {}^{L}\!/_{N^2} \tag{11}$$

$$c = {}^{L}\!/_{N(N-1)} \tag{12}$$

$$c = {}^{2L}\!/_{N(N-1)} \tag{13}$$

*Generalization* ($G$) – The average number of prey eaten per predator in a web. One generates this value by adding column sums in the food web matrix [**F**] and dividing this figure by the number of columns with non-zero elements (the number of predators). Generalization represents the number of prey species that a species can consume (Pimm 1982, Schoener 1989).

$$G = {}^{L}\!/_{n_{predator}} \tag{14}$$

*Vulnerability* ($V$) – The average number of predators per prey in a web. In a manner similar to generalization, one adds the row sums in the food web matrix [**F**] and divides by the total number of rows with non-zero elements (the number of prey) to find vulnerability. Vulnerability represents the number of predator species against which a species can defend (Schoener 1989).

$$V = {}^{L}\!/_{n_{prey}} \tag{15}$$

*Cyclicity* ($\lambda_{max}$) – A measure of the strength and presence of cyclic pathways present in the system (Fath and Halnes 2007). Cyclicity is obtained by finding the maximum real eigenvalue of a web's structural adjacency matrix [**A**]. The adjacency matrix in Figure 11a is a structural depiction of a network with six species.

$$\begin{array}{c} \text{Columns} \\ \mathbf{A} = \begin{array}{cc} \begin{array}{cccccc} \text{i} & \text{ii} & \text{iii} & \text{iv} & \text{v} & \text{vi} \end{array} & \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} & \begin{array}{c} \text{i} \\ \text{ii} \\ \text{iii} \\ \text{iv} \\ \text{v} \\ \text{vi} \end{array} \end{array} \text{Rows} \end{array} \qquad \det(\mathbf{A}\text{-}\lambda\mathbf{I})=0 \qquad \lambda = \begin{bmatrix} 0 \\ -1 \\ 1i \\ -1i \\ 1 \\ 0 \end{bmatrix} \qquad \lambda_{max} = 1$$

**(A)** **(B)** **(C)** **(D)**

Figure 11: The process for calculating the cyclicity of a system with six species. (a) Labeled adjacency matrix for the system– rows represent flow *to* a node, columns *from* a node. (b) Equation for the calculation of the eigenvalues for the adjacency matrix. (c) Eigenvalues. (d) The cyclicity of the cycle as the maximum real eigenvalue of the adjacency matrix. *Figure used with permission from* (Layton, Reap et al. 2012).

The eigenvalues of a matrix are mathematically defined as the solutions to equation 16, the determinant of the quantity of the matrix in question minus the eigenvalues times the identity matrix of the equivalent size, all equal to zero. The result of equation 16 is a set of eigenvalues (which may be both real and imaginary). The maximum real eigenvalue in this set is the cyclicity of the food web represented by matrix **A** (Borrett, Fath et al. 2007). The maximum real eigenvalue ($\lambda_{max}$) is a measure of the proliferation of pathways that connect two nodes in a network. There is a greater potential for flows to remain within the system as pathways proliferate, and so $\lambda_{max}$ is indicative of the resulting internal cycling [17].

$$\det\left(\mathbf{A}-\lambda\mathbf{I}\right)=0 \tag{16}$$

The use of eigenvalues to determine cyclicity (also known as “pathway proliferation rate”) of a system combines results from graph theory and linear algebra (Borrett, Fath et al. 2007). The proof presented by Borrett et al. uses the Perron-Frobenius theorem, which guarantees that there is only one real eigenvalue that is greater than or equal to all other eigenvalues ($\lambda_1 \geq \lambda_i$ for $i = 2 \ldots n$) in adjacency matrices associated with a strongly connected network (Borrett, Fath et al. 2007). In networks where it is possible to reach every node from every other node only the maximum (dominant) eigenvalue is left to represent the pathway proliferation rate of the system as the limit of the number of indirect links (pathways between two nodes which consist of more than one link) goes to infinity.

Cyclicity can be either 0, 1 or greater than 1.This is illustrated in Figure 12, which is based on the similar figure by Fath and Halnes (Fath 1998, Fath and Halnes 2007). Zero cyclicity indicates that no internal cycles are present, Figure 12a. In these networks energy traveling through the system never passes through a component twice. A value of one is representative of a network where only simple closed loop pathways exist, Figure 12b. Those networks which have cycles made up of one link (self-loops) or have cycling only if link-direction is ignored, may have a maximum eigenvalue of either 1 or 0 (Borrett, Fath et al. 2007). A network with a maximum eigenvalue greater than one indicates that the network is made up of complex looped pathways, as described in Figure 12c. The larger the cyclicity the more complex and numerous the paths are between components, creating a system that is more interconnected. Most food webs are composed of networks where large subsets of “nodes” are strongly connected such that the maximum eigenvalue is greater than one, indicating the existence of multiple cyclic pathways.

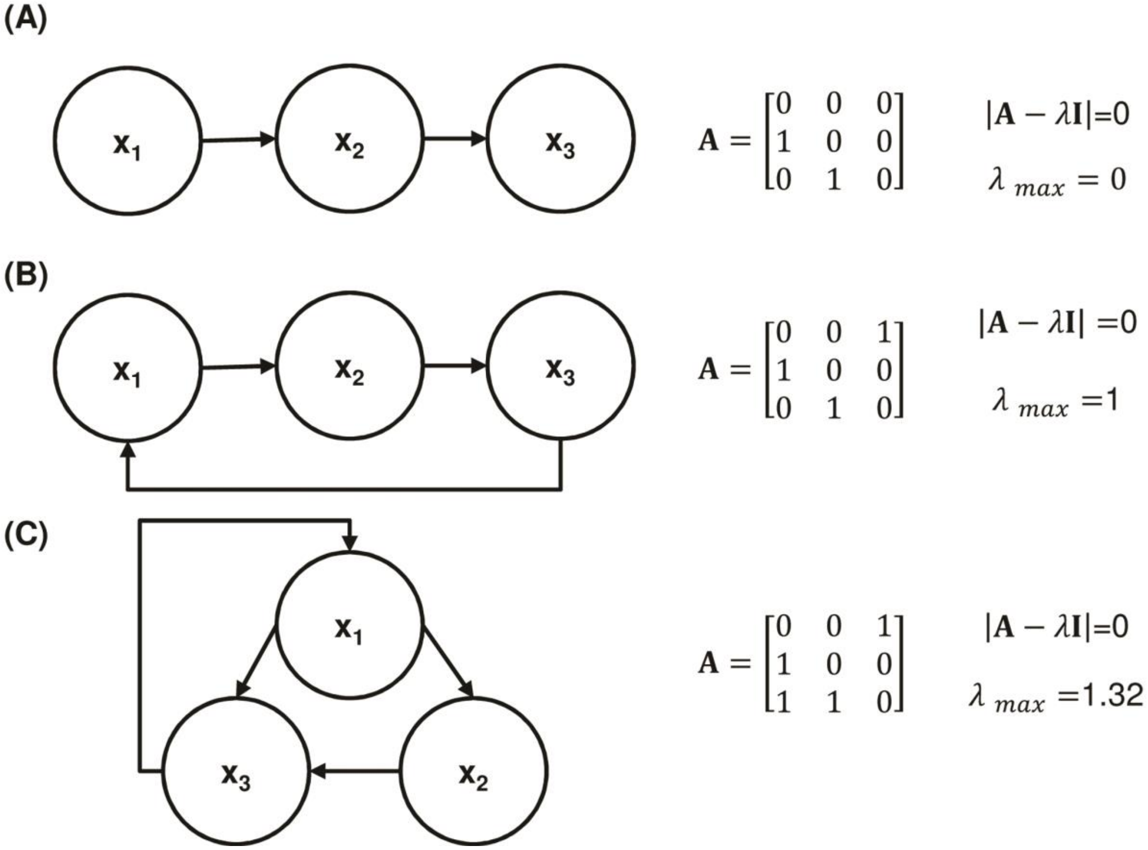


Figure 12: Examples of the three types of internal structural cycling based on cyclicity (eigenvalues). (a) No cycling $\lambda_{max} = 0$, (b) weak cycling $\lambda_{max} = 1$, (c) and strong cycling $\lambda_{max} > 1$. *Figure used with permission from* (Layton, Reap et al. 2012).

With respect to cyclicity, the dynamics and stability of food webs are significantly influenced by nutrient recycling and decomposition (McCann 2012). In ecosystems, the detritivores (earthworms, fungi, and bacteria for example) are responsible for the decomposition of dead organic matter (DOM) and the distribution of nutrients to the system, often known as the “recyclers of the biosphere.” This decomposition and redistribution create a fixed cyclic structure in the system as measured by cyclicity (Husar 1994).

### 3.4 Effects of Different Organizing Matrices

The organizational matrix used to represent the system can have a significant impact on the results of an ecological analysis. The matrix chosen also impacts the food web data that may be used in comparisons. The metric connectance (equations 11-13 in section 3.3.2) in particular is impacted by the choice or organizing matrix as well as assumptions made for the system, specifically whether or not cannibalism is assumed to be possible. These two choices when made influence whether equation11, 12, or 13 is to be used in the calculation of connectance. The choices made should be noted for the sake of comparisons made against previous EIP and FW results. The literature is full of ecological analyses of EIPs done using one set of assumptions and then compared to food webs analyzed using another set of assumptions. Fath and Halnes use equation 11 with the food web matrix (Fath and Halnes 2007). Briand uses equation 12 with the higher well-defined estimate community matrix [$\mathbf{C_U}$] to analyze his set of 40 biological food webs in his 1983 paper (Briand 1983), as do Briand and Cohen in 1987 (Briand and Cohen 1987) and Schoener in 1989 (Schoener 1989). Briand notes that this method "yields a relatively high estimate of the connectance (Briand 1983)." Yodzis, who's method Briand follows, notes that if non-food related interactions are assumed to be "less common than interactions involving food resources, then $c_U$ [calculated from the higher well-defined estimate of the community matrix] can be regarded as something like an upper bound on connectance. Otherwise it can simply be regarded as an estimate which is arrived at in a well-defined way (Yodzis 1980)." Warren in 1990 (Warren 1990) uses equation 12 as well but with the food web matrix [**F**]. Hardy and Graedel use equation 13 with the food web matrix [**F**] in their analysis of industrial systems in 2002 (Hardy and Graedel 2002). This gave them lower connectance values ($c_L$), whereas the ecological food webs they were comparing their industrial networks to, those from Briand 1983, had the higher well-defined connectance values ($c_U$). The method used by Hardy and Graedel for calculating connectance is described by Yodzis such that "If we know all the feeding relationships in a community, we can determine in this way a set of community matrix elements which are certainly non-zero, whence a lower bound ($c_L$) on the connectance (Yodzis 1980)." It is very important that both the connectance equation used and the matrix connectance is used with are explicitly stated when calculating and comparing these structural measures and metrics.

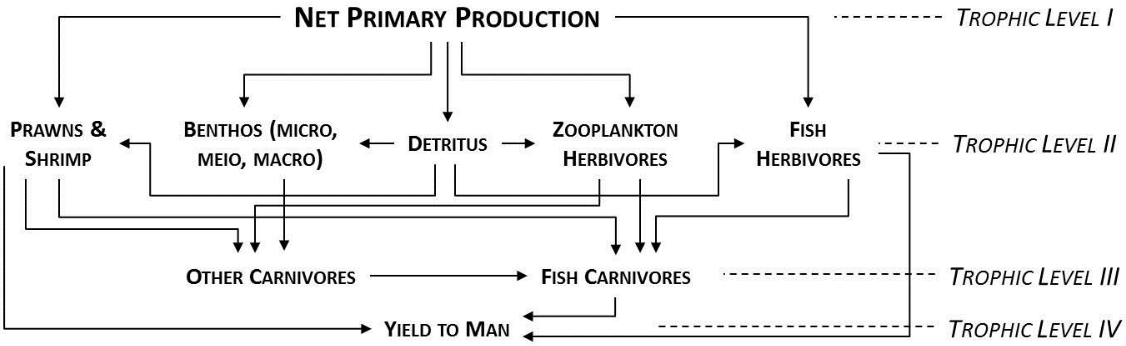


Figure 13: Generalized representation of a food web in the Cochin estuary showing interactions across multiple trophic levels. *Adapted from* (Qazim 1970).

As an example of the effects matrix choice, species organization, and connectance equation used all have the Cochin estuary of Figure 13 will be used. The Cochin estuary is used by both Briand in 1983 and Briand and Cohen in 1987 (Briand 1983, Briand and Cohen 1987). There are at least 18 different ways to define one's matrix and calculate connectance (one ecological metric used here for the purpose of the example) from the Cochin estuary. Table 3 shows that a very small variation in the number of species in the system ($N$) can produce a relatively large variation in metrics calculated therefrom. The system definitions used by Briand, Cohen and Qazim are compared against additional alternatives such that all three matrices introduced in section 3.3.1 are used. Two additional options were also explored: 1) regarding the inclusion of flows to the detrital actor and 2) the choice to define man as a species, the result of which causes $N$ to vary between 8 and 9. Table 3 documents the different combinations possible and shows that the value of the ecological metric connectance varies as a result from 0.25 to 0.857, as significant spread considering a seemingly insignificant change in the number of actors represented. Connectance is important to system designers as it is believed to influence system properties such as stability and robustness. Combined with linkage density, species number, and prey to predator measurements, connectance helps represent system complexity (Dunne, Williams et al. 2002).

Table 3: Differences in definition of the Cochin estuary to species, links, and connectance. "All" flows to detritus include all species except man. "Minimal" flow to detritus follows the flows outlined by Qasim in Figure 13. [$\mathbf{C_U}$] stands for high well-defined estimate community matrix, [$\mathbf{C_L}$] stands for lower estimate community matrix, and [**F**] stands for food web matrix(*man is counted as a species here but primary production is not counted).

| **Definition** | **Man = species?** | **Flow to detritus?** | **Matrix used?** | **Species (S)** | **Links (L)** | **Connectance (c)** |
|---|---|---|---|---|---|---|
| (Briand 1983) | yes | none | $C_U$ | *9* | *50* | *0.694* |
| (Briand 1983) | yes | none | F | *9* | *18* | *0.25* |
| (Briand and Cohen 1987) | yes | none | F | *8** | *14* | *0.25* |
| (Qazim 1970) | yes | minimal | F | *9* | *19* | *0.264* |
| Alternate 5 | no | minimal | F | *8* | *16* | *0.285* |
| Alternate 6 | yes | all | F | *9* | *23* | *0.319* |
| Alternate 7 | no | all | F | *8* | *20* | *0.357* |
| Alternate 8 | yes | none | $C_L$ | *9* | *32* | *0.444* |
| Alternate 9 | no | none | $C_U$ | *8* | *15* | *0.268* |
| Alternate 10 | no | none | $C_L$ | *8* | *30* | *0.536* |
| Alternate 11 | yes | minimal | $C_L$ | *9* | *38* | *0.528* |
| Alternate 12 | yes | minimal | $C_U$ | *9* | *52* | *0.722* |
| Alternate 13 | no | minimal | $C_L$ | *8* | *32* | *0.57* |
| Alternate 14 | no | minimal | $C_U$ | *8* | *44* | *0.786* |
| Alternate 15 | yes | all | $C_L$ | *9* | *46* | *0.638* |
| Alternate 16 | yes | all | $C_U$ | *9* | *58* | *0.806* |
| Alternate 17 | no | all | $C_L$ | 8 | 40 | 0.714 |
| Alternate 18 | no | all | $C_U$ | 8 | 48 | 0.857 |

The study of eco-industrial parks primarily concerns analyzing industrial networks and comparing them to biological networks. Table 3 clearly shows that the assumptions used for the biological analysis must be well understood in order for the industrial networks to have analogous assumptions applied allowing for an accurate comparison.

## 3.5 Misconceptions in the Current Food Web Analogy

The current industrial ecology model is problematic; there are logical inconsistencies in the use of the food web analogy. Inaccurate industrial definitions for ecological terms result in fundamental inaccuracies in industrial ecology and ineffective biological analyses of industrial systems. To the extent that analogies between natural and artificial systems are used in an explanatory or predictive manner, key ecological phenomenon must be accurately transcribed to similar processes and phenomenon in industrial systems. This requires an understanding the ecological process and how components of the process are measured, described, and organized.

### 3.5.1 Species, Function, and the Ecological Niche

The Burnside Industrial Park in Halifax, Nova Scotia is investigated by Wright *et al*. The group measures  diversity in the system using the metrics species evenness and species richness defined in section 3.3.2 (Wright, Côté et al. 2009). What Wright and team fall short of fully comprehending is the conceptual meaning of species evenness vs. species richness (outlined in Figure 10).

System definitions are highly important to the food web analogy in order to calculate metrics and obtain meaningful information. Burnside Park is first defined in terms of a structural analogy. This is problematic in that it clouds the necessary functional analogy. To highlight the importance of species function ecologists frequently aggregate species in a system into trophic species. Unfortunately ecologists tend to drop the descriptor ‘trophic’ early on, or do not use it all together and as a result it has been overlooked by many food web analyses of EIPs. Species evenness and species richness for Burnside Park are calculated based on the definitions that every company in the park is a unique species thus there is only one of each, and the organisms, or populations of each species, in the park are the workers in each company (Wright, Cote et al. 2009). This results in high species richness and arbitrary species evenness. This is a structural analogy and not a functional one is that it is not the workers who are interacting in the industrial ecosystem, it is the companies. The value or activity of the company is only weakly correlated, if at all, with worker number. So if each company is one species, an attribute needs to be defined such that it represents the *abundance* of that species. Otherwise when this definition is used there is no way to account for diversity: diversity will always seem maximal when species is defined such that it is represented by one individual.

The function of diversity is to account for both the number of species and their proportional representation in a community. Ecologists use diversity because if a single species is dominant (measured by species evenness) in a system with many different types of species, then the community is less varied than the number of species (measured by species richness) would otherwise imply (Purvis and Hector 2000). An economic definition of diversity is the number of sectors in the system which use energy, and the equitability of the energy flows between them (Templet 1999). Despite the debates amongst ecologists over the connection between diversity and other system properties in food webs e.g. (McCann 2000, Tilman 2000, Chase and Leibold 2002, Dunne, Williams et al. 2002, Hooper, Solan et al. 2002, Garmestani, Allen et al. 2006, Buzhdygan, Rudenko et al. 2010), industrial ecologists have used an analogy with food webs that positively connected diversity to the enhancement of connectedness e.g. (Jelinski, Graedel et al. 1992, Allenby and Cooper 1994, Graedel 1996, Korhonen and Snäkin 2005, Korhonen and Seager 2008, Wright, Côté et al. 2009) and efficient energy use e.g. (Daly 1996, Costanza, Cumberland et al. 1997, Templet 1999).

One definition of species groups together organisms with very similar requirements, meaning that each individual can be considered roughly equal, allowing species to be a unit of analysis. Individuals in a species, as defined in ecology, have the same niche (way of life or set of requirements) and or genetic continuity. This designation is important as it makes species an evolutionary unit. The two definitions (similar niche, interbreeding population) reinforce each other, but which is more useful depends on the specific question being asked. Nonetheless the key is collapsing individuals into a single unit for analysis. Therefore, if we wish to apply ecological principles to EIPs, we need to use species in IE in a way that is functionally equivalent to its use in ecology.

> "*The analogous entity for species in an industrial system is subject to debate. As companies are diverse (in terms of their specific products, raw materials, and markets), it can be argued that each company is the equivalent of a species in nature. Alternatively, as facilities in the same industry sector have nearly identical resource requirements, perform similar material transformations, and have comparable types of waste streams, it can also be argued that an industry sector is the equivalent of a species in nature.*" (van Berkel 2009)

An understanding of the ecological niche in industrial ecology would be of great assistance to van Berkel here (van Berkel 2009). There are numerous species with similar inputs and outputs that are still classified as different species. While it is true that no two species can have exactly the same requirements and coexist, what is lost in this statement by van Berkel is that what is consumed or transformed is not the only thing of importance in defining species; ratios of resources, location of resources, etc. are all part of what make two possibly similar organisms separate distinct species. The warbler bird umbrellas a number of different individual bird species, and if based upon dominant characteristics such as appearance and intake/output they may be grouped together under one title, there are very important variations in the foraging locations within a tree that warrants them to be separated as distinct species in their own right (MacArthur 1958).

Every analysis of EIPs sets each individual company in the industrial network to be a unique species without considering the function of each company, Figure 14-Left. Take for example a hypothetical industrial network that contains four peanut plants. This network using the current industrial definition of species is translated into a network with four actors. Following the ecological definition of diversity however (a combination of species richness and evenness) this network would not be considered diverse.

Were each peanut plant to import peanuts and produce peanut butter then their functional roles would be the same and they would be all the same species. If however one plant were to shell peanuts, one to roast them, one to produce peanut butter, and one to distribute the final product they would each have a unique functional role and be labeled individual species, this would be represented by the species definition of Figure 14-Right.

This is an important organizational tool in ecosystems: resources are not only things that are consumed or transformed and what is consumed or transformed is not the only important defining characteristic. For many plants the ratios of resources used or provided are important, while for birds, such as the warblers, it is not what they eat but where their influence is that defines them.

Thus species cannot be arbitrarily equated to each company in an industrial network. The properties that are fundamentally important to the running of the industrial park or process should also be considered before proceeding with the defining of species and other ecological definitions. Detailed information regarding the functions of the actors in an industrial network is often not available. As a result of this information gap, the current method of defining each company in an EIP as a unique species can be used as it presents a conservative estimate of the cycling and diversity in the system.

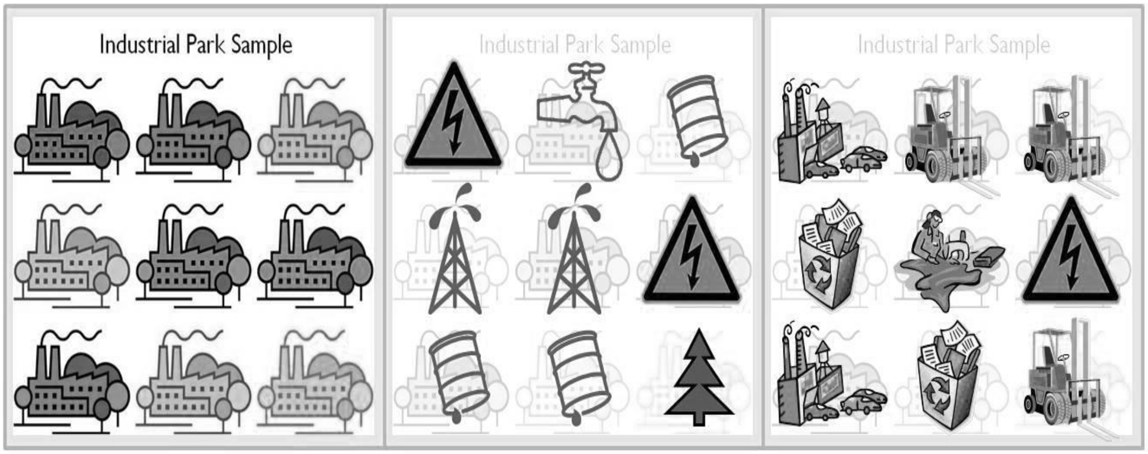


Figure 14: Three different species definitions for a hypothetical industrial park. Left: each company in the industial park is a species. Center: species in the industrial park is defined by the type of input of each company. Right: species in the industrial park is defined by the function of each company.

### 3.5.2 Omnivory and Recycling

An ecosystem is comprised of cyclic paths that form a web-like structure with no top predator, as highlighted in Figure 15. This structure results in multidimensional and multidirectional interactions characteristic of omnivory and recycling. These components are believed to be a significant influence on the structural robustness of ecosystems. Despite the importance and prevalence of these specific exchanges (Patten 1985), they are consciously ignored in the industrial model. Uninformed statements are made that species operate between distinct trophic levels and their exchanges are unidirectional and the image of a ‘food chain’ reoccurs throughout the literature.

> *“Omnivory is common in nature, but it complicates the food chain diagram without adding conceptual insight, so it is not incorporated…”* (Graedel 1996)

> *“… species in ecosystems operate with distinct trophic levels, and physical exchanges between species are therefore unidirectional, which leads to food chains. Industrial enterprises can operate at different trophic levels for their different material flows (end consumer of fuel and intermediate consumer for product raw materials). Industries can also have bidirectional resource exchanges (a furniture manufacturer could be a supplier of wood waste to and a consumer of electricity from a biomass power plant) .”* (van Berkel 2009)

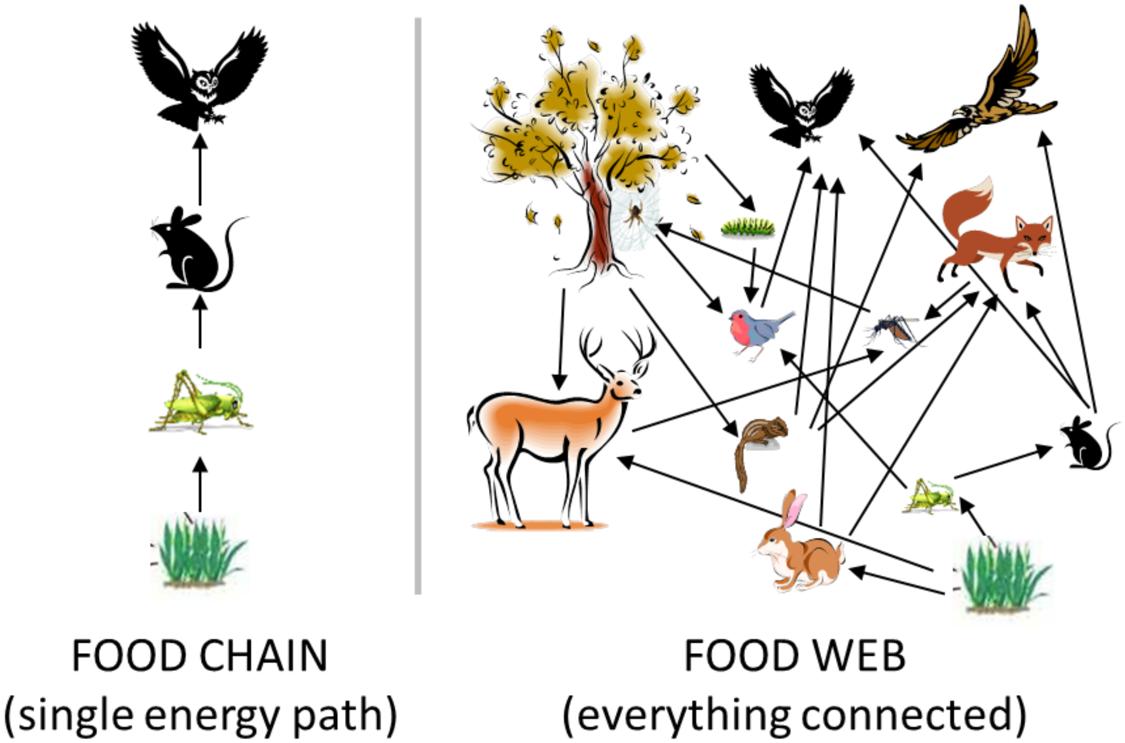


Figure 15: A dramatization of the difference in complex cyclical interactions between a food chain and a food web in nature. Adapted from (deCharon 2013).

Recycling accounts for only small fraction of mobilized matter in industry, the result being that recyclers not economically important (Husar 1994). This is in sharp contrast with the huge importance of the analogous decomposer system, detritivores and decomposers, in ecosystems. The cycling created by this important group is believed to be a major contributor to the robustness and efficiency of ecological systems (Hardy and Graedel 2002). As a group detritivores are fundamentally different from other functional groups present – they allow energy to flow unrestricted to any location in the system and process a large percentage of the total system energy (Odum 1969). For example, in a mature forest less than 10% of the annual net production is consumed in a living state, most is used as dead matter (detritus) through delayed and complex pathways (Odum 1969).

Most of the materials and energy in an ecosystem are transferred from the producers to the recyclers, only a small percentage passes through the consumers. The recyclers in turn process almost all of the material in the system and return it for reuse (Townsend, Begon et al. 2008). Figure 16 shows the importance of different pathways in four ecological cycles through the relative size of the boxes and arrows representing the compartments and flows in each system. The decomposer/detritivore pathway may see five times the energy flux as other pathways, reaffirming the idea that this functional group is invaluable (Townsend, Begon et al. 2008).  This is not necessarily the case for industrial systems where recyclers are most often not economically important and the materials and energy circulating in the system rarely pass through this type of actor (Husar 1994). There is no economic sense in passing primary materials and energy directly from producers to recycling actors (Husar 1994), there are almost always byproducts in the production of anything however and this matter can very effectively be rerouted from a dead end location to a recycling facility. Most of the successful exchanges in EIPs with high levels of internal cycling are due to byproducts being recycling and returned to the system by some form of recycler. These actors are wastewater treatment plants, processing facilities, compost generators, and agriculture-type actors.

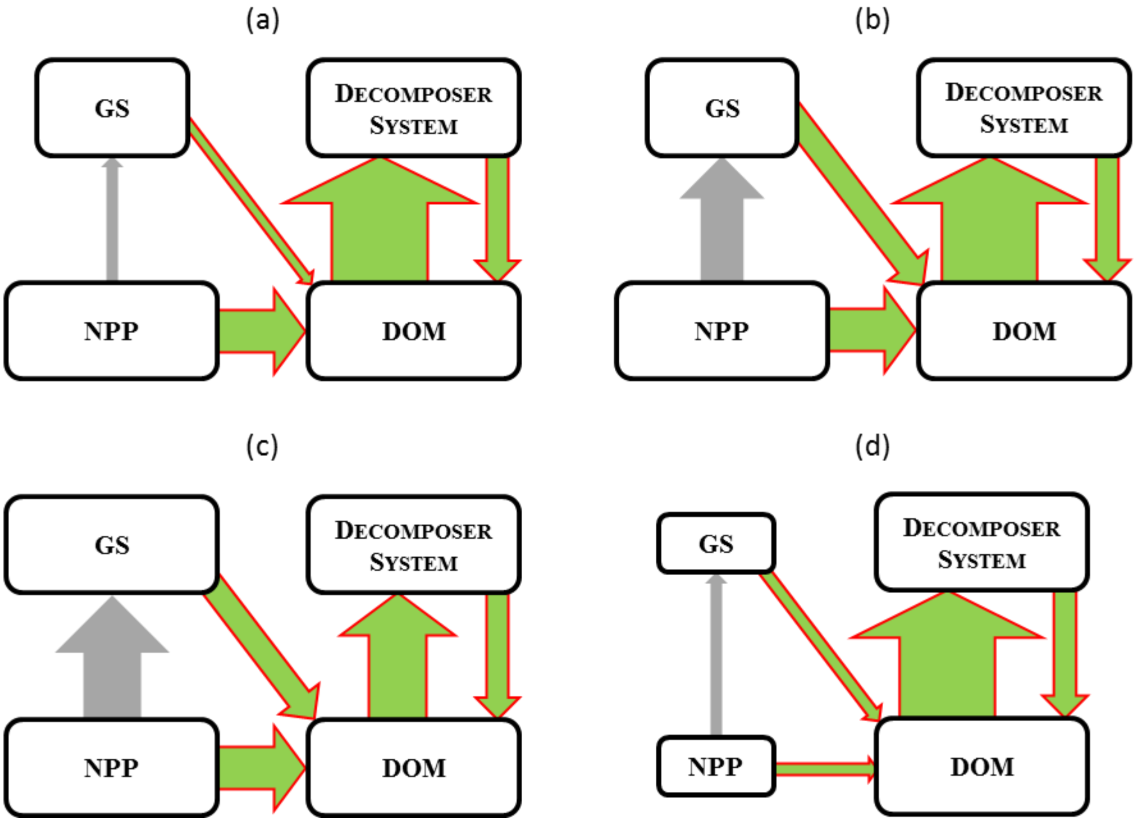


Figure 16: Proportional energy flows between sub-systems in four ecological cycles; (a) forest, (b) grassland, (c) plankton community in the sea, and (d) the community of a stream or small pond. The relative size of the boxes and arrows are proportional to the relative magnitude of the compartments and flows. NPP = net primary production; GS = grazer system, also known as the live consumer system; DOM = dead organic matter; Decomposer System = decomposers and detritivores. *Figure adapted from* (Townsend, Begon et al. 2008) and *used with permission from* (Layton, Reap et al. 2012).

### 3.5.3 Physical Proximity

Ecosystems can have a physical proximity that is becoming more uncommon in today’s global economy, this does not necessarily rule out any and all analogies with food webs though. Korhonen and Snäkin argue that ecosystems have no global flows or connections while industrial networks are never totally isolated or closed (Korhonen and Snäkin 2005). Husar makes the point that this proximity results in very little energy expenditure in the physical transport of materials and energy between actors and allows for fast reaction and adjustments in the face of system perturbations (Husar 1994). The energy expenditures of transportation in an industrial setting however may not be that distinct from the energy which an animal must expend to track down its prey. Some ecosystems span the globe: storks for example are relatively heavy birds which migrate from Northern Europe to South Africa extending their system boundaries over 12,000km (van den Bossche 2005). Infrastructure and transportation are becoming more cost effective, and often times once in place can result in minimal energy requirements.

## 3.6 Conclusions

One of the goals of sustainable design is to match production to the reusable resources available. Using nature as a model, a system that already has this structure in place, can aid in this goal.

The first step in building an industry model to mimic food webs is to translate the model set up from the analogous system to the system of interest. The definition of species in the network should not unconscientiously be equated to each present company. The properties that are fundamentally important to the running of the industrial park or process should also be considered when possible before proceeding with the defining of species and other ecological quantities. Detailed information regarding the functions of the actors in an industrial network is often not available however and as a result of this information gap, the current method of defining each company in an EIP as a unique species can be used as it presents a conservative estimate of the cycling and diversity in the system.

With species defined the network can be described by one of three matrix representations that have been translated for use with industrial networks. Of those matrices translated, the food web matrix [**F**] has been recommended for use in industry design. This matrix meets the requirements for the calculation of ecological metrics therefrom, and its entries are easily populated by industrial systems.

Once the system has been translated into the appropriate form measures and metrics from the analogous biological system may be applied. Fourteen ecosystem measurements are presented to aid in the comparison of industrial systems to ecosystems, ultimately providing design guidance to industry decision makers. Properties such as complexity, stability, robustness, and system dynamics may all be described through combinations of the fourteen measures translated here. System complexity may be measured through a combination of linkage density, species number, and prey to predator measurements, and connectance. System stability may be influenced by the metrics connectance and cyclicity. The makeup of the types of relationships in the system is represented by the metrics regarding the prey to predator ratio, the fraction of specialized predators in the system, and the metrics generalization and vulnerability which summarize the requirements the system places on its consumers and producers.

Many aspects of food webs have not yet been translated to industry, partially due to a lack of understanding in industry of the ecological modeling process. Some have been purposefully ignored because it was not understood how to apply the properties to an industrial setting. This chapter translates important properties to industry and addresses existing misconceptions. Two misunderstandings overshadow all others, one regarding species definition and the other regarding the organizing matrix. Individual species in ecosystems, when condensed to a food web representation are often aggregated into trophic species. Ecologists when referring to species in food webs will drop the signifier ‘trophic’ causing much confusion for those in industry using food webs as comparators. Small variations in definition of key system properties, such as in the number of species in the system ($N$), can produce significant variation in metrics calculated therefrom. The type of matrix used to represent the system can also have a significant effect on the resultant metric calculations. Chapter 3 shows the effect that species aggregation and matrix representation has on these calculations.

# CHAPTER 4

# CYCLICITY APPLIED TO THERMODYNAMIC POWER SYSTEMS

## 4.1 Research Questions to be Addressed

A thorough literature review on ecosystems and food web analyses thereof has repeatedly expressed the importance of the structural metric cyclicity. Here, cyclicity is further investigated in a more familiar context, by applying it to twenty eight (28) familiar thermodynamic power systems of increasing complexity. Complexity increases the number of times initial energy in the system is cycled, so it may be reused to reduce the potential heat or work lost and required, thereby decreasing the dependence on outside power. This seems to align with the circuitous structure of food webs favored by nature. As cyclicity is a measure of the existence and strength of this internal structural cycling of energy (Allesina, Bodini et al. 2005, Fath 2007, Fath and Halnes 2007) we test if cyclicity can also be used as a measurement tool in thermodynamic power systems, while we explore potential associations with both traditional measures of efficiency and the structure of engineered systems. The application gives a more clear understanding of the meaning of high or low cyclicity and addresses the research goal of identifying fundamental physical relationships behind the correlation between ecosystem structural patterns and environmentally superior industrial network designs.

## 4.2 Methods

### 4.2.1 Thermodynamic Power Systems

Ecosystems are often referred to in light of the second law of thermodynamics, that the entropy of an isolated system cannot decrease (Odum 1969, Schneider and Kay 1994, Sonntag, Borgnakke et al. 2003). Thermodynamic power systems are a natural comparison to food webs in that they have very similar structural properties; both systems are defined by inputs, outputs, and exchanges between the system components and both transform materials and energy, maturing towards higher system efficiency. Power systems transform energy (in the form of temperature and pressure) in the working fluid into work and heat through a series of processes from some initial state (Sonntag, Borgnakke et al. 2003). Twenty eight (28) well documented thermodynamic power systems of increasing complexity are used to investigate the ecological metric cyclicity. The benefits to using thermodynamic power systems to test ecological analysis techniques are that power cycles have well understood properties and processes, everything may be known and documented, including structure and flow, and the networks have well established evaluation techniques. The two power systems used are the Brayton cycle and the Rankine cycle, both in their idealized forms. The ideal Brayton cycle is a thermodynamic power cycle used to model the gas turbine engine. The Brayton cycle in its most basic form consist of a compressor, a combustion chamber, and a turbine, with any leftover heat released to the surroundings. Work and heat are required inputs to the compressor and combustion chamber, and work is produced by the turbine. The ideal Rankine cycle is a thermodynamic power cycle that is the simplest representation of the vapor power cycles utilized by the electric power generating industry. The Rankine cycle in its most basic form consists of a pump, a boiler, a turbine, and a condenser. Work is required by the pump and heat is required by the boiler, while work and heat are produced by the turbine and condenser respectively. The two power cycles mature towards higher efficiencies through he inclusions of feedwater heaters, regeneration, reheating and intercooling: all standard ways of increasing thermal efficiency (Sonntag, Borgnakke et al. 2003).

#### 4.2.1.1 Thermal Efficiency

All thermal efficiencies ($\eta_I$ in equation 17) and pertinent state point data were calculated using Engineering Equation Solver (EES) version V8.881-3D. The maximum and minimum cycle temperatures and pressures or pressure ratios were kept constant throughout the modified cycles for consistency, as described in Table 1. Extraction pressures for the feedwater heaters were chosen on a per cycle basis to maximize the thermal efficiency of each cycle. The work and heat externally supplied to the power cycle, $W_{in}$ and $Q_{in}$ respectively, and the work produced by the power cycle, $W_{out}$, were calculated based upon enthalpies (*h*) at pertinent inlet and exit points (outlined by equations 18-20). For more information on calculating work, heat, and the thermal efficiency for thermodynamic power cycles please see a thermodynamic reference book such as Sonntag, Borgnakke, and van Wylen's *Fundamentals of Thermodynamics* (Sonntag, Borgnakke et al. 2003).

$$\eta_I = \frac{\sum_i \left(W_{out,i} + W_{in,i}\right)}{\sum_i \left(Q_{in,i}\right)} \tag{17}$$

$$W_{in,i} = \left(h_{exit} - h_{inlet}\right)_{compressor,\,pump} \tag{18}$$

$$W_{out,i} = \left(h_{exit} - h_{inlet}\right)_{turbine} \tag{19}$$

$$Q_{in,i} = \left(h_{exit} - h_{inlet}\right)_{boiler,combustor} \tag{20}$$

Table 4: Specified state point data for all ideal Rankine and Brayton cycle analyses.

| **Rankine Cycles - water** | **Brayton Cycles - air** |
|---|---|
| $T_{min}$= 318.9 K | $T_{min}$ = 288.2 K |
| $T_{max}$ = 873.2 K | $T_{max}$ = 1273 K |
| $P_{pump1,input}$ = 10 kPa | $P_{compresser,input}$ = 100 kPa |
| $P_{boiler,input}$ = 15000 kPa | $r_p$=10 (pressure ratio) |

### 4.2.1.2 Conversion to Energy Flow Networks

To uncover the internal cycling present in the system we must first use the network approach in thermodynamics to construct a graphical model revealing system topology, referred to here as an energy flow network (Oster, Perelson et al. 1971). In this approach mechanical components are considered ‘nodes’ in the network representing the power cycle (a node is a system component that receives and-or transmits energy). Connections between nodes occur when energy embodied in the working fluid as well as internal exchanges of work and heat flow from one node to another. Work and heat entering the cycle from outside are not considered. We analyzed twenty (20) standard variations on the ideal Rankine cycle and eight (8) standard variations on the ideal Brayton cycle. Only one of the ideal cycles is covered here in detail as the procedure was the same for all cycles used. Figure 17*b* recasts the familiar equipment diagram of an ideal Rankine cycle with one open feedwater heater, seen in Figure 17*a*, as a set of nodes joined by energy exchanges. Starting in the lower left corner of Figure 17*a*, one sees that energy, in the form of shaft work, at Pump 1 enters the system raising the energetic state of the working fluid above that found at State 1 (the reference state for this energy flow network), this translates into the link between node 1 and node 2 in Figure 17*b*. Energy carried by the working fluid flows to the open feedwater heater where it combines with another energy flow in the form of steam bled from the turbine. The network continues the transferring, adding and subtracting of energy as the working fluid moves between ideal components. With the power cycles recast as energy flow networks, we need only to write the structural adjacency matrix and compute its maximum real eigenvalue to determine cyclicity for each cycle.

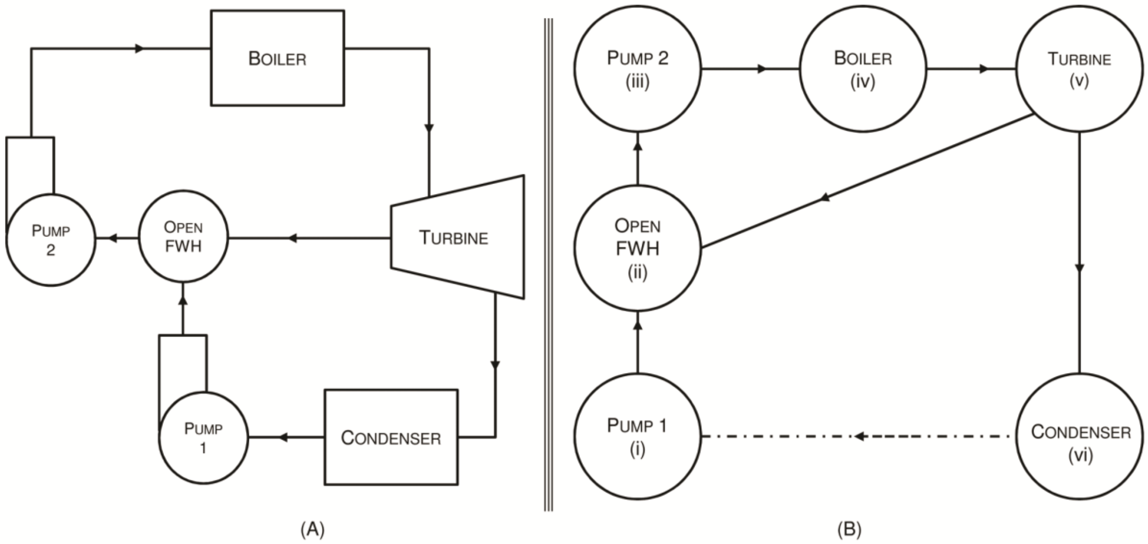


Figure 17: Ideal Rankine power cycle with one open feed water heater redrawn as energy flow networks following thermodynamic network theory (Lewis 1995). Note that the link between the condenser (Node vi) and Pump 1 (Node i) is not a physical flow of energy. Since State 1 acts as an energetic reference state for the network, working fluid returning to that reference state only closes the *material* loop; energy embodied in the working fluid leaving the condenser is rejected to the surroundings.) *(a) Energy, in the form of heat and work and carried by the working fluid, flows to and from the mechanical components of the idealized equipment diagram for a power cycle. (b) The system is simplified with the mechanical components modeled as 'nodes' connected by flows of energy in the energy flow diagram.*

### 4.2.2 Cyclicity

Cyclicity, as outlined in section 3.3.2, is an older metric reintroduced by Fath and Halnes that measures the presence and strength of cyclic (closed loops as opposed to linear chains) pathways also known as "strongly connected components" in a system (Allesina, Bondavalli et al. 2005, Borrett, Fath et al. 2007, Fath 2007). Unlike the cycling index (CI), a flow metric that also quantifies the amount of cycling in the system, cyclicity does not require knowledge of flow magnitude, only flow path (Odum 1969, Finn 1976). Flow magnitude information can be quite complex, if not impossible, to acquire for an ecosystem thus cyclicity is a highly useful and simple metric. Flow magnitude information is also very difficult to obtain for an industrial system as this information is often highly proprietary so a purely structurally-based metric is beneficial in the analyses of EIPs as well.

To review from section 3.3.2, cyclicity is calculated by determining the maximum real eigenvalue of the adjacency matrix, as determined by equation 16. Cyclicity can be zero (0), one (1) or greater than one (1), as represented by Figure 12 (the figure is reprinted here as Figure 18 for the readers benefit). The higher the cyclicity of the system the more interconnected its components and the greater the potential for existing flows of materials and energy to remain within the system.

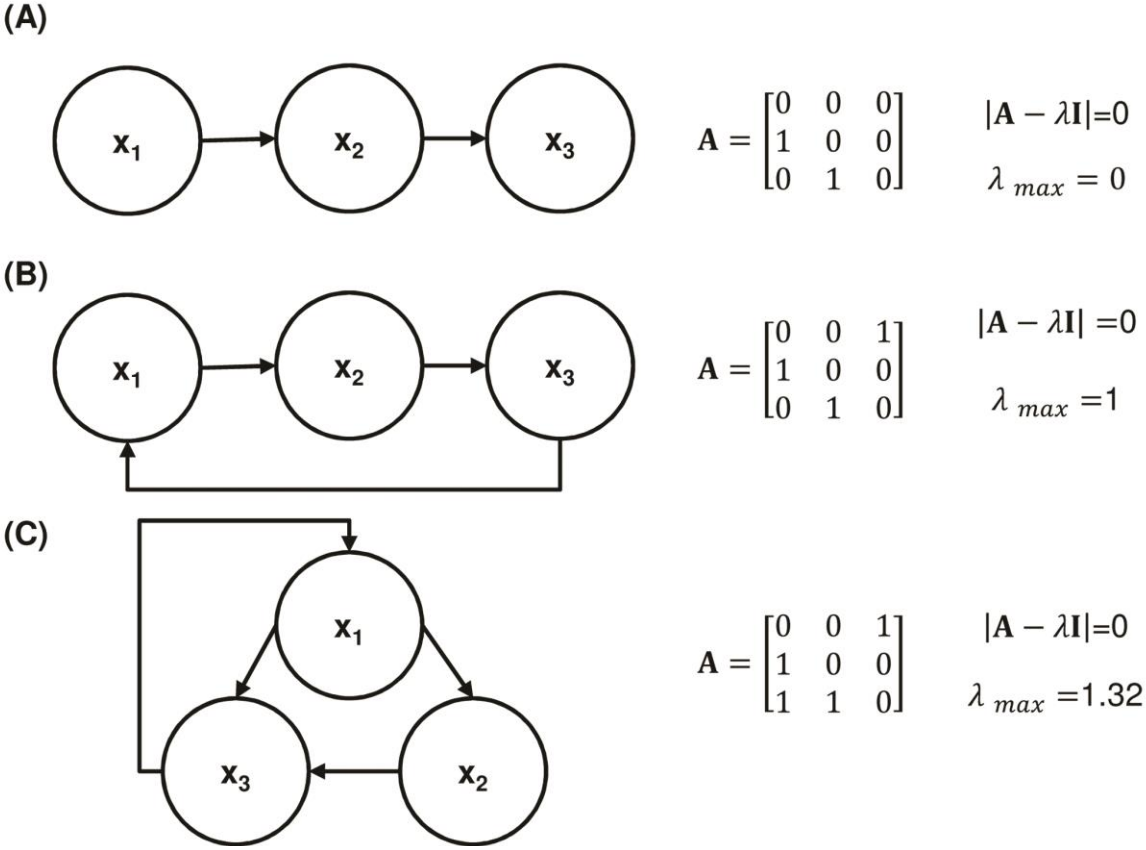


Figure 18: Examples of the three types of internal structural cycling based on cyclicity (eigenvalues). (a) No cycling $\lambda_{max} = 0$, (b) weak cycling $\lambda_{max} = 1$, (c) and strong cycling $\lambda_{max} > 1$. *Adapted from* (Fath 1998, Fath and Halnes 2007).

#### 4.2.2.1 Maximum Eigenvalue

With the power cycles now in matrix form, cyclicity is found by calculating the maximum real eigenvalue ($\lambda_{max}$) for each corresponding adjacency matrix [**A**] as described by equation 16 in section 3.3.2. MATLAB's "*eigs*" function was used to execute this task (MATLAB R2011b, Atlanta, Georgia).

### 4.3 Results

Analysis of twenty eight variations on the ideal Brayton and Rankine cycles shows a positive correlation between cyclicity and the maximum thermal efficiency. The compiled values for cyclicity and thermal efficiency, as well as the specific modifications made to the Brayton and Rankine cycles can be found in Table 5 and Table 6. Figure A70 - Figure A75 in Appendix A offer additional insights into the modifications made. The results of these two tables are displayed in Figure 20. The Brayton cycle, by design, gives higher thermal efficiencies than the Rankine cycle, and modifications to the Brayton cycle produce a much larger increase in thermal efficiency than for the Rankine cycle; the addition of one extra component in each (reheat in the Rankine cycle, **R2** in Table 5, and regeneration in the Brayton cycle, **B2** in Table 6) results in a 16.8% increase in thermal efficiency for the Brayton cycle but only a 4.7% increase for the Rankine cycle. Both are desirable, even a small increase in efficiency in practice is highly sought after.

Table 5: Thermal efficiency and cyclicity values for 20 (R1-R20) ideal Rankine power cycles evaluated under the same conditions.

| **Cycle** | **Thermal Efficiency ( $\eta_I$ )** | **Cyclicity ( $\lambda_{max}$ )** |
|---|---|---|
| **(R1)** Basic Rankine | 0.430 | 0 |
| **(R2)** Rankine with reheat | 0.451 | 1 |
| **(R3)** Rankine with 1 closed FWH trapped condensate | 0.453 | 1 |
| **(R5)** Rankine with 1 open FWH | 0.463 | 1 |
| **(R6)** Rankine with 2 open FWHs | 0.472 | 1.15 |
| **(R7)** Rankine with 1 closed FWH pumped condensate | 0.453 | 1.17 |
| **(R8)** Rankine with 3 open FWHs | 0.476 | 1.21 |
| **(R9)** Rankine with 1 open and 1closed FWH | 0.476 | 1.30 |
| **(R10)** Rankine with 4 open FWHs | 0.479 | 1.24 |
| **(R11)** Rankine with 5 open FWHs | 0.480 | 1.25 |
| **(R12)** Rankine with 6 open FWHs | 0.482 | 1.26 |
| **(R13)** Rankine with 7 open FWHs | 0.482 | 1.27 |
| **(R14)** Rankine with 8 open FWHs | 0.483 | 1.27 |
| **(R15)** Rankine with reheat and 1 open FWH | 0.470 | 1.27 |
| **(R16)** Rankine with reheat and 2 open FWH | 0.483 | 1.33 |
| **(R17)** Rankine with reheat and 3 open FWH | 0.488 | 1.43 |
| **(R18)** Rankine with reheat and 4 open FWH | 0.491 | 1.44 |
| **(R19)** Rankine with reheat and 5 open FWH | 0.492 | 1.45 |
| **(R20)** Rankine with reheat and 6 open FWH | 0.493 | 1.45 |

***FWH, feed water heater**

Table 6: Thermal efficiency and cyclicity values for 8 (B1-B8) ideal Brayton power cycles evaluated under the same conditions.

| **Cycle** | **Thermal Efficiency ( $\eta_I$ )** | **Cyclicity ( $\lambda_{max}$ )** |
|---|---|---|
| **(B1)** Basic Brayton | 0.482 | 1.00 |
| **(B2)** Brayton with Regeneration | 0.563 | 1.22 |
| **(B3)** Brayton with regeneration, intercooling, and reheat (2 turbines) | 0.685 | 1.39 |
| **(B4)** Brayton with regeneration, intercooling, and reheat (3 turbines) | 0.718 | 1.46 |
| **(B5)** Brayton with regeneration, intercooling, and reheat (4 turbines) | 0.733 | 1.50 |
| **(B6)** Brayton with regeneration, intercooling, and reheat (5 turbines) | 0.742 | 1.52 |
| **(B7)** Brayton with regeneration, intercooling, and reheat (6 turbines) | 0.748 | 1.53 |
| **(B8)** Brayton with regeneration, intercooling, and reheat (7 turbines) | 0.751 | 1.54 |

The vapor power cycles utilized for the generation of 90% of all electric power used throughout the world are modeled by the Rankine cycle (Jorgensen and Nielsen 1998, Wiser 2000). The Brayton cycle is used to model the gas turbine engine. The theoretical upper bound for the efficiency of these and any other real or ideal heat engines is the Carnot efficiency, equation 21. The Carnot efficiency represents the maximum possible work that may be done between any two temperatures and is independent of the working substance used or any particular design feature of the engine, as represented by Figure 19. One could continue to increase the number of links added thereby increasing the cyclicity; however, the Carnot efficiency ($\eta_C$) will not be reached. The Carnot efficiency, although physically unattainable, is useful in that it gives us an upper limit to strive for. If the efficiency of a real engine is significantly lower, then additional improvements may be possible. More information on efficiencies and power cycles can be found in any thermodynamic reference book, for example *Fundamentals of Thermodynamics* by Sonntag, Borgnakke, and van Wylen (Sonntag, Borgnakke et al. 2003). The Carnot efficiency for the Rankine and Brayton cycles analyzed are 0.635 and 0.774 respectively. We will specify all thermal efficiencies as either maximum Rankine or Brayton cycle efficiencies or Carnot efficiency. The Carnot efficiency creates a ceiling which will lead to a logarithmic-type relationship relating cyclicity to the maximum thermal efficiency if infinite data points were used. Modifications made to real world systems, which must deal with irreversabilities (also known as losses, such as friction), will eventually become cost ineffective in that the addition of feedwater heaters, regeneration, reheating and intercooling will no longer increase cycle efficiency, for example once 8 feedwater heaters are in place in a Rankine cycle (Kadem 2007).

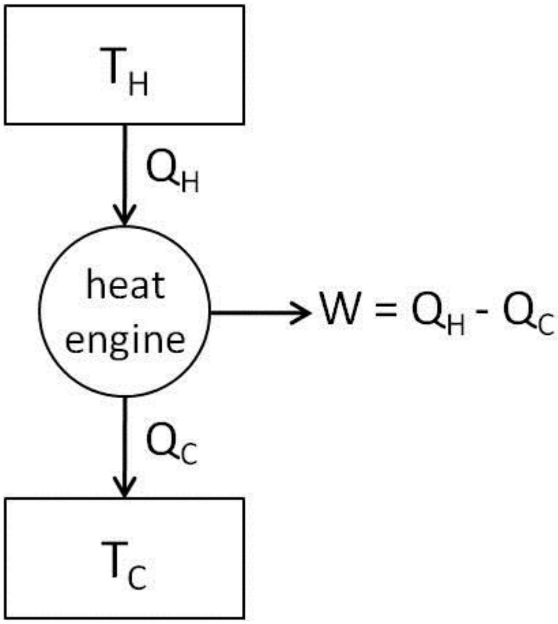


Figure 19: A Carnot heat engine, representing the maximum possible work produced between two temperature reservoirs, which is the most efficient possible heat engine. The Carnot efficiency (equation 21) is derived from this ideal heat engine.

$$\eta_C = 1 - \frac{T_{\min}}{T_{\max}} \tag{21}$$

There is a clear lack of data points between the values of zero and one for cyclicity in the Rankine cycles due to the nature of cyclicity being zero, 1, or greater than 1. This constraint makes it impossible to drastically increase the $R^2$ value, or coefficient of determination, by obtaining data between the cyclicity values of zero and 1. Including all cycle points (Figure 20) $R^2$ values for the linear trend lines are 0.988 and 0.768 for Brayton and Rankine cycles respectively. The $R^2$ value, for the Rankine cycle increases to 0.818 if we focus on those cycles which are greater than or equal to one (the Brayton cycles all contain some amount of internal structural cycling and therefore are unaffected by this refocusing).

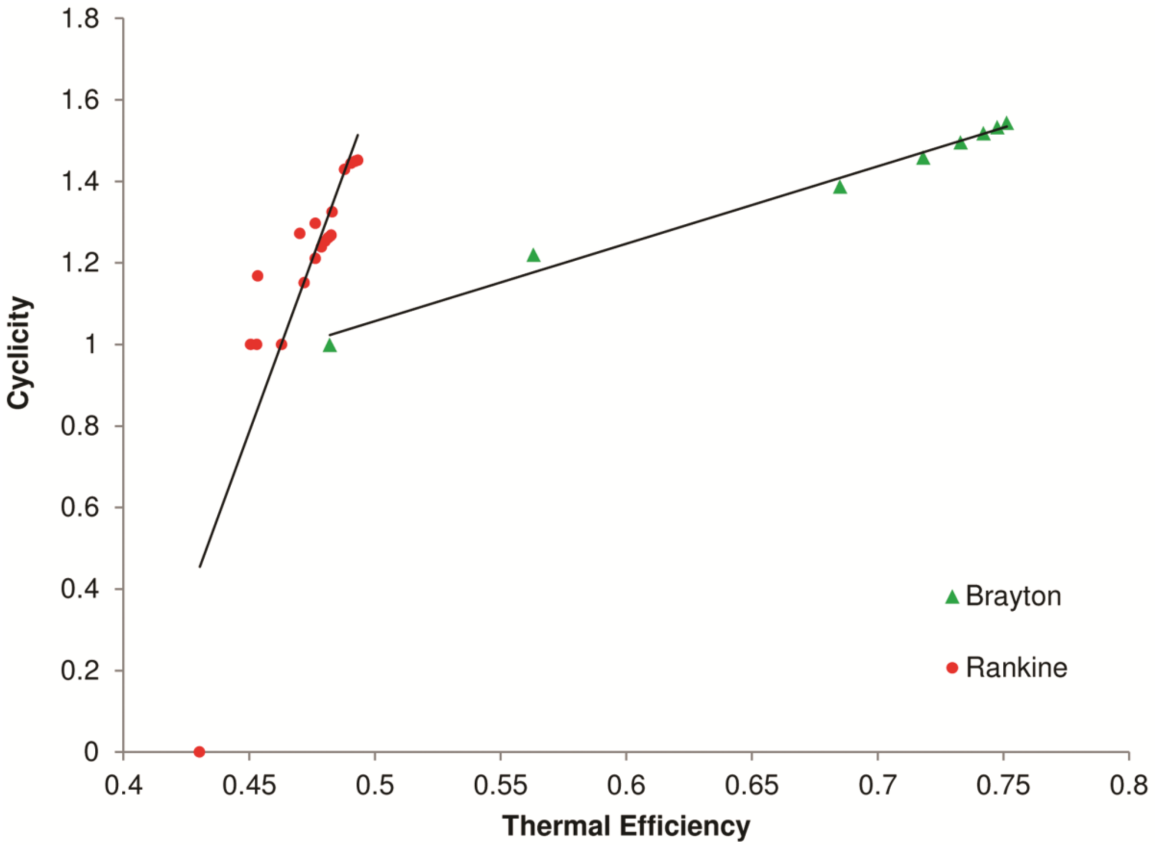


Figure 20: Maximum Thermal Efficiency vs. Cyclicity for all 28 Power Cycles with linear trend lines. Note: All cycles described here are ideal and optimized for maximum thermal efficiency; changes in kinetic and potential energy from one point to another have been neglected as well as losses in connections between components, such as friction losses in pipes, turbulence, and flow separation.

### 4.4 Discussion

Nature's networks and mankind's power cycles must both obey the Laws of Thermodynamics, but connecting the two often proves less than straightforward. The non-equilibrium perspective used to describe ecosystems emphasizes the capacity of complex systems to dissipate energy internally such that they are able to maintain their organization in a physical gradient (Schneider and Kay 1994, Ho 1998). The application of cyclicity to thermodynamic power cycles tests the correlation between non-equilibrium (ecosystem – cyclicity) and equilibrium (thermal efficiency – power cycles) thermodynamic measures by computing both measures in the same system. High cyclicity values relate strongly to the overall proportion of the energy retained vs. that which is lost by the system, qualities that may translate to more robust and efficient industrial networks. This analysis concludes that cyclicity can accurately predict maximum thermal efficiency for both the Rankine and Brayton power cycles and that increasing cyclicity in energetic networks is associated with, or perhaps partially driven by, the maximization of thermodynamic work. The positive correlation, ranging from 0.88 to 0.99, found here between the two measures makes sense: the structural complexity created by measures taken to increase thermal efficiency result in increasing the amount the working fluid is cycled as well. Looking at the figures in Appendix A one sees that the additional components added to the power systems increase the total amount of available energy used within the system by adding internal cycles. The most basic Brayton cycle (seen in Figure A73) has the working material pass through the system once; all energy left at the end of the path is discarded. The more complex Brayton cycles (Figure A75, for example) add components, and thereby linkages, such that the working material is cycled back through the system at different points, using energy that would have otherwise been discarded. These added components act as recyclers, analogous to the function of fungi and similarly operating species in an ecosystem – processing low grade materials and energy so it can be cycled back into the system.

Odum in his paper *The strategy of ecosystem development* in 1969, observed that the cycling of energy in food webs increases with system maturity, with the bulk of the biological energy flow following detritus pathways (Odum 1969). He cites for example a mature forest, where less than 10% of the annual net production is consumed (by grazing) in a living state, most is used as dead matter (detritus) through delayed and complex pathways. Detrital pathways, particularly in mature forests, are composed of low quality energy inputs since the dominant plant biota contain large amounts of relatively refractory structural material. The additional components in the thermodynamic systems that cycle the “waste” energy (the energy not used in the most basic form of the Rankine and Brayton cycles) back through the system could be considered an analogous detrital component. The “waste” energy is low quality in comparison to the initial energy in the working fluid at the start of the cycle, which can be deemed high quality. The more complex Rankine and Brayton power cycles may be said to be structurally analogous to a mature ecosystem, both have greater structural complexity allowing for more energy to be cycled internally (Schneider and Kay 1994, Ho 1998). This reiterates from a thermodynamic perspective the importance of a recycling component to the efficient use of materials and energy in a network.

Additionally, the application of cyclicity to power cycles has shown that the relative potential efficiencies of power cycles may be determined by relative cyclicity values. When comparing two modifications to the same cycle it is a great deal easier to calculate cyclicity than to carry out a complete thermodynamic analysis. If cycle A has a higher cyclicity than cycle B, the correlation found here would lead the investigator to believe that cycle A has the potential for a higher maximum thermal efficiency. The analysis also suggests that Brayton and Rankine power cycles differ in the extent to which each may be improved by changing the connectivity of its components. The efficiency of the Brayton cycle from this analysis is extremely sensitive to how interconnected its components are with respect to the transfer of energy. The linear trend lines and coefficients of determination in Figure 20 reveal that less than 2% of the thermal efficiency of a Brayton cycles depends on things other than the internal structural cycling of energy. The thermal efficiency for a Rankine cycle is somewhat less affected by its structural cyclicity, leaving about 23% of the efficiency to depend on other factors. This relative behavior of Rankine and Brayton cycles is characteristic of the types of modifications that can be made to each. This behavioral difference can be explained in ecological terms: the Brayton cycle has more system components that act as recyclers – sending low quality energy that would otherwise be at the end of its life back to the actors at the start of the cycle (the high quality energy users – or primary producers in ecological terms).

### 4.5 Conclusions

The correlation between non-equilibrium (ecosystem – cyclicity) and equilibrium (power cycles – thermal efficiency) thermodynamics is tested through the application of cyclicity to thermodynamic power cycles. Cyclicity is shown here to accurately predict maximum thermal efficiency for both the power cycles tested. This results in the conclusion that increasing cyclicity in energetic networks is associated with, or perhaps partially driven by, the maximization of thermodynamic work. The positive correlation between cyclicity and thermodynamic efficiency is also a validation of the assumption that designing networks to look and operate more like ecosystems results in increases in efficiency. Specifically the correlation suggests that having high cyclicity values, similar to food webs, results in higher network efficiencies. This correlation also reconfirms the importance of recyclers or detritus/decomposers to the operation and structure of ecosystems, and the ability to at least partially measure their presence using cyclicity. Cyclicity will be used as the leading organizing metric for EIPs collected and analyzed as a result of these findings.

# CHAPTER 5

# INDUSTRIAL ECOSYSTEMS AND FOOD WEBS: STRUCTURAL ANALOGY - OR - WHAT MAKES AN EIP GOOD OR BAD?

## 5.1 Research Questions to be Addressed

Eco-industrial parks (EIP) have become a popular manifestation of sustainable initiatives around the world. The essential unknown is what makes an EIP good or bad? The research questions aimed at acquiring this basic understanding are:

1) What is preventing EIPs from successfully imitating food web structure and function?
2) How can industrial ecology further progress toward these ecological design goals?

A detailed and complete set of eco-industrial parks case studies is an important component of this work and key goal to answering the research questions posed here. There are very few papers and internet resources which survey real (existing and failed) and proposed EIPs and apply an ecological analysis to them, and there is no one paper that covers everything out there. A dataset of food webs that is both current and ecologist approved to use for comparisons with the EIPs is also necessary to answering the questions posed.

Through analyses and comparisons between EIPs and FWs, the fundamental physical relationships responsible for the correlation between bio-inspired network patterns and environmentally superior industrial network designs may be identified. The identified success factors build towards the creation of sustainable design guidance for closed-loop industry networks.

## 5.2 Datasets: Eco-Industrial Parks and Food Webs

Comprehensive datasets of food webs and eco-industrial parks are needed to perform the analyses required to address to research questions posed above.

### 5.2.2 Food Web Dataset

#### 5.2.2.2 Food Web Data Collection Techniques

Appendix B outlines the food webs used in this dissertation, which were collected through literature reviews. Literature used included, but was not limited to, articles from various industrial ecology minded journals, industry media releases, conference proceedings and presentations, and reviews. The three main datasets were made up of 69 FWs from Briand and Cohen as listed in (Briand 1983, Briand and Cohen 1987), 17 FWs from Dunne as listed in (Borrett, Fath et al. 2007), and 58 FWs from Borrett as listed in (Borrett 2013). Additional literature was used to confirm specific ecosystems details such as species represented, species aggregation, year collected, and linkages. The literatures used for this purpose were found in the papers containing the original datasets listed above. The number of actors and linkages and the food web matrices were taken from the literature. From these three pieces of information the rest of the metrics investigated were calculated and additional information was gleaned, such as the existence of a detrital actor and linkages to and from said actor, and the number of cannibalistic interactions. Using the original sources Table B53 was created using only those food webs which had been collected on or after 1993, a collection of 50 FWs. This follows the work of Cohen et al. and Pimm which pointed out inconsistencies and problems in ecosystem collection and documentation techniques (Martinez 1991, Pimm, Lawton et al. 1991, Cohen, Beaver et al. 1993). These two pieces of literature caused a measurable shift in the quality of the ecosystem data collected.

#### 5.2.2.3 Food Web Data Analysis Methods

Despite the importance of flows to and from the detritivores (Husar 1994, Moore, Berlow et al. 2004, Allesina, Bondavalli et al. 2005, Fath and Halnes 2007, Halnes, Fath et al. 2007) (Townsend, Begon et al. 2008), food web analyses do not always include detrital flow. Some of the food webs which were taken from the 1983 collection by Briand were modified following the method of Fath and Halnes to address this omission (Briand 1983, Fath and Halnes 2007). Food webs that had an existing, explicitly listed detritus species, were modified such that connections from all other species in the system to the detritus were added as most material normally passes through detritus in typical natural systems. The food webs that were modified are also included in their original format, all of which may be found in Appendix B. Modified food webs have been labeled with an *M* signifying that it was modified from its original reference state to include links to the detritus.

The 144 food webs were also sorted and plotted in terms of those with a detritus component (70 food webs - *FWD*) and those without (74 food webs - *FWND*), due to the importance of the detritivores and decomposers in the cycling of materials and energy in a food web. Food web complexity is an important property and is partially measured using the metric connectance, which is highly dependent on whether cannibalism is possible in the system, see equations 11, 12 and 13. The impact of cannibalistic interactions on the structure of a food web lead us to sort and plot the food webs as those with documented cannibalism (53 food webs - *FWC*) and those without (90 food webs - *FWNC*) as well. The food webs have also been sorted into those collected prior to 1993 (94 food webs - *FWPre*) and those collected after 1993 (50 food webs - *FWPost*) in response to the shift in collection and documentation techniques and the greater emphasis placed upon the quality of food web data amongst ecologists since the early 1990's (Polis 1991, Cohen, Beaver et al. 1993).

### 5.2.3 Eco-Industrial Park Dataset

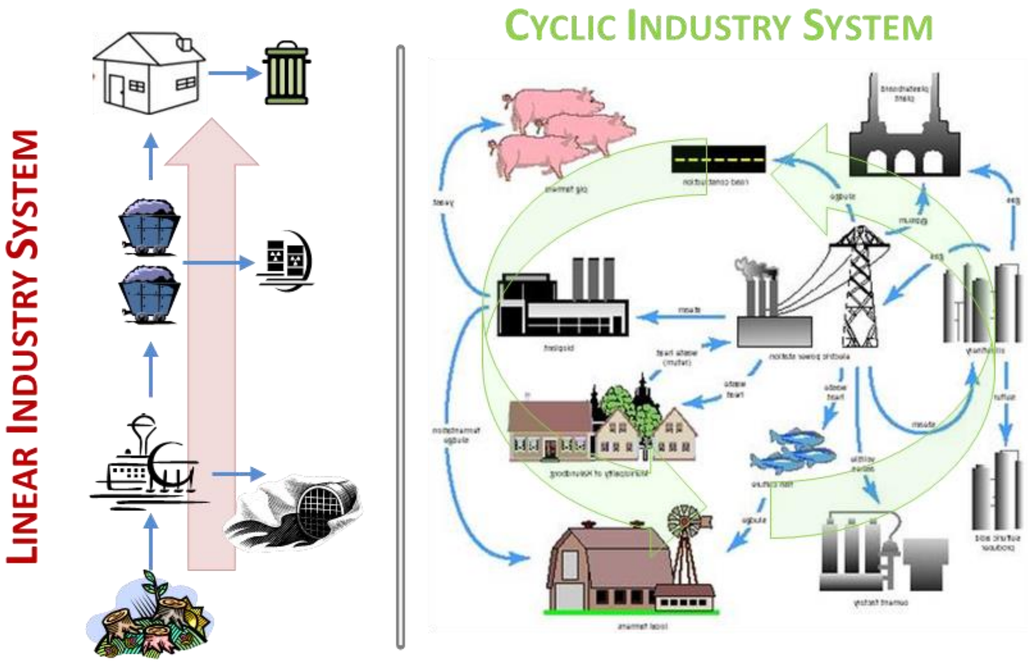


Figure 21: Linear vs cyclic industry systems.

### 5.2.3.2 EIP Data Collection Techniques

The information in Appendix C was collected through thorough reviews of the literature and internet searches. Literature used included, but was not limited to, articles from various industrial ecology minded journals, industry media releases, conference proceedings and presentations, and reviews. Internet searches included, but were not limited to, news articles, company and EIP websites, graphics, university groups with focuses on sustainable design, EIP advocacy groups and government initiatives. Essentially three datasets have been created. The first data set given in Table C54 provides more general information: a collection of names, locations, references, brief descriptions, and whenever possible the current status and/or proposal year. The information in Table C54 provides a better sense of those parks which exist around the world but for which detailed information may not be readily available. The second can be found in Appendix D and is comprised of those EIPs for which structural data was found. Structural information includes information on the physical linkages between companies, such as the two industrial actors being connected, what materials and/or energy is being exchanged, and the amount being exchanged (most likely in the units of amount/yr.). With the most basic structural data, information on the physical connections, structural metrics used by ecologists are applied to analyze the EIPs. The third dataset can be found in Appendix F and comprises those few EIPs with information on the mass flows of the linkages. With this information additional and more complex metrics and analysis methods used by ecologists are applied. Unfortunately much of this information is proprietary and so was very difficult to obtain, hence the limited number of EIPs in this third dataset.

#### 5.2.3.3 EIP Data Analysis Methods

We compare the 48 collected EIPs to an updated ecological dataset consisting of 144 food webs deemed to be of high quality by ecological standards. The results of the metrics applied to the collected food webs and EIPs are given in Figure 22 and collected in Table D55. The 48 collected EIPs (EIP) are plotted in Figure 22 alongside all 144 collected ecological food webs (FWA). Figure 22 plots the information using box plots, which highlights the median value for each dataset, as well as the overall distribution of the data and intervals from which a statistical difference between medians may be said to be of significance. The box is created using the 25th and 75th percentiles of the data as the top and bottom, and the line drawn within the box is the median, calculated as the 50th percentile. The percentiles are calculated such that 25, 50, or 75 percent of the data is falls below each value respectively. The triangles represent intervals for which two medians may be said to be statistically different at the 5% significance level if the intervals do not overlap. The crosses in the plots are the outliers of each dataset, defined as such if they are larger than [q3 + 1.5(q3 – q1)] or smaller than [q1 – 1.5 (q3 – q1)], where q1 and q3 are the 25th and 75th percentiles and n is the number of data points in the set. The intervals are calculated as [q2 ±

$1.57(q3 - q1)/\sqrt{(n)}]$, where q2 is the 50th percentile. Table 9 highlights statistical differences in median values between the EIP dataset and the FWA dataset for each of the metrics plotted in Figure 22. If the notch intervals do not overlap between the two datasets then we can say that the two medians are statistically different at a 5% significance level, or in other words that the two medians can be said to be different with 95% confidence.

Food web matrices [**F**] for the 48 industrial parks, listed in Appendix E, were used to calculate each of the 10 ecological metrics defined in section 3.3.2, equations 1-16. All 48 EIPs were analyzed following the same process as outlined for Kalundborg. Ten food web metrics for each ecological food web were calculated and assessed: species richness, links, connectance, linkage density, prey, predators, prey-predator ratio, vulnerability, generalization, and cyclicity. Additionally connectance was calculated from both equations 11 and 12 (with and without cannibalism respectively).

#### *5.2.3.3.1 Ecosystem Network Analysis Applied to Eco-Industrial Parks*

EIPs and industrial ecosystems can be represented by food web diagrams; in the industrial representation the predator-prey exchanges between species become the exchanges of materials and energy between companies. One simply substitutes an industrial facility for each species and an industrial resource flow for each link. For example, the companies within the Kalundborg EIP become species 1-17, and the links documented between them become the exchanges, represented by the squares and connectors respectively in Figure 6. The resultant food web matrix for the representation of Kalundborg follows in Table 7. With this analogy in place many of the metrics used by ecologists may be applied to analyze and influence the structure, and thus behavior, of industrial networks. For example the complexity of an ecosystem is measured through the density of its linkages, the quantity and types of species, and the systems connectance (Dunne, Williams et al. 2002). The use of statistical summaries of these and other metrics as a guide for the development of EIPs has been suggested as a way to form both cost effective and sustainable industrial networks

(Reap 2009). Structural metric values calculated from equations 1-16 for Kalundborg are listed in Table 8 alongside averages for food web with and without listed detrital components. We can see that despite the touted successes of Kalundborg: over 30 material and energy streams between companies, reducing yearly $CO_2$ emission by 240 kilo-tons, and saving 264 million gallons of water through recycling and reuse (Roberts 1976), the EIP falls closer to averages seen for those food webs without detrital components, and is far from the averages for the food webs with detrital components.

Table 7: The Food Web Matrix [**F**] representation of the Kalundborg EIP (shown in Figure 6).

| | | **To Process # -- Consumer/Predator** | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **From Process # -- Producer/Prey** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** |
| **Farms** | **1** | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Inbicon** | **2** | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Lake Tisso** | **3** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Statoil** | **4** | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Fertilizer Industry** | **5** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Kara/Noveren** | **6** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Cement Industry** | **7** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Gyproc** | **8** | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Nickel Industry** | **9** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **DONG Energy** | **10** | *0* | *1* | *0* | *1* | *0* | *0* | *1* | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *1* |
| **Kalundborg Forsyning** | **11** | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* |
| **Wastewater Treatment Plant** | **12** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* |
| **Purification Plant** | **13** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| **RGS 90** | **14** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Novo Nordisk & Novozymes** | **15** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *1* | *0* |
| **Pig Farms** | **16** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **Fish Farms** | **17** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table 8: Ecological Metrics calculated from the Food Web Matrix in Table 7 for the Kalundborg EIP of Figure 6 compared with ecological food web (with and without a detrital component) averages.

| | ***N*** | ***L*** | ***$L_d$*** | ***c*** | **# Predators** | **# Prey** | **# Specialized Predators** | ***$P_R$*** | ***$P_S$*** | ***G*** | ***V*** | ***$\lambda_{max}$*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Kalundborg EIP* | 17 | 24 | 1.41 | 0.09 | 15 | 10 | 10 | 0.67 | 0.67 | 1.60 | 2.4 | 1.95 |
| *Food Web median w/ detritus* | 25 | 99 | 3.91 | 0.19 | 21 | 25 | 3 | 1.11 | 0.086 | 3.40 | 4.16 | 3.67 |
| *Food Web median w/o detritus* | 15 | 37 | 1.96 | 0.13 | 13 | 13 | 4 | 1.06 | 0.139 | 2.33 | 2.43 | 1.00 |

Current EIPs will most likely follow some properties of biology's naturally sustainable systems through inter-company relationships, but overall these networks as they are currently designed still have a ways to go to meet the resilient and efficient properties of nature's long maturing networks (Reap 2009).

### 5.3 Results: Comparisons of Eco-Industrial Parks and Food Webs

Determining the causal differences that prevent industrial systems from functioning like natural systems is necessary in order to evaluate and understand how ecological principles may inform the organization of industrial systems. Using appropriate ecological data and analysis we show that eco-industrial parks are not constructed, and consequently do not function, like their food web analogs, supporting prior conclusions (Reap 2009). This more thorough understanding becomes a potential source of insight regarding how to structure and analyze industrial organization.

Most structural parameters investigated here show that EIPs are less complex than their ecological counterparts. Many of the metrics used here normalize measures for the network size. These metrics show that the limited complexity of EIPs appears to be a trend unrelated to scale. Compared to their food web analogs, each company in an EIP has fewer connections to other companies in the network ($L_D$) and there are more companies that use resources and energy (predators) than there are companies within the network that provide those resources and energy (prey) as seen in the prey to predator ratio ($P_R$). The later observation highlights that eco-industrial parks tend to have one or a few companies act as the key source of materials and energy for the rest of the members. The average numbers of links per prey ($V$) and per predator ($G$) are significantly lower in EIPs than food webs.

Connectance was found here to be the only food web metric in the group that did not behave as expected (that food webs would outperform the EIPs was hypothesized), similar to what was found by Hardy and Graedel (Hardy and Graedel 2002). There is no statistical difference in median connectance values between *EIP* and *FWA*, calculated from both equations 11 and 12; the median values for EIPs are actually slightly higher. Looking at equation 11, we see that $N$ is squared in the denominator. Consequently, in a mathematical sense, a network with more actors will have a significantly smaller connectance than a network with few actors, even if its linkage density is much larger. For example, a network with 8 actors and 20 links will have a more favorable connectance than a network with 80 actors and 200 links. Thus food webs with large $N$ values are essentially handicapped in comparison with EIPs when using connectance. To fairly make comparisons we must focus on networks with similar numbers of species ($N$). When we focus on those food webs of similar size to the EIPs ($N < 30$), the median connectance for food webs (with cannibalism) is greater than EIPs, increasing from 0.158 to 0.178. Additionally limiting our food webs to those collected after 1993, the median connectance (with cannibalism) increases yet again to

0.208. Connectance is potentially an important design parameter as it can tell us about the overall structure, complexity, and robustness of the system (Dunne, Williams et al. 2002, Dunne, Williams et al. 2002). Thus it is important to note that comparisons using connectance must focus on networks of similar sizes.

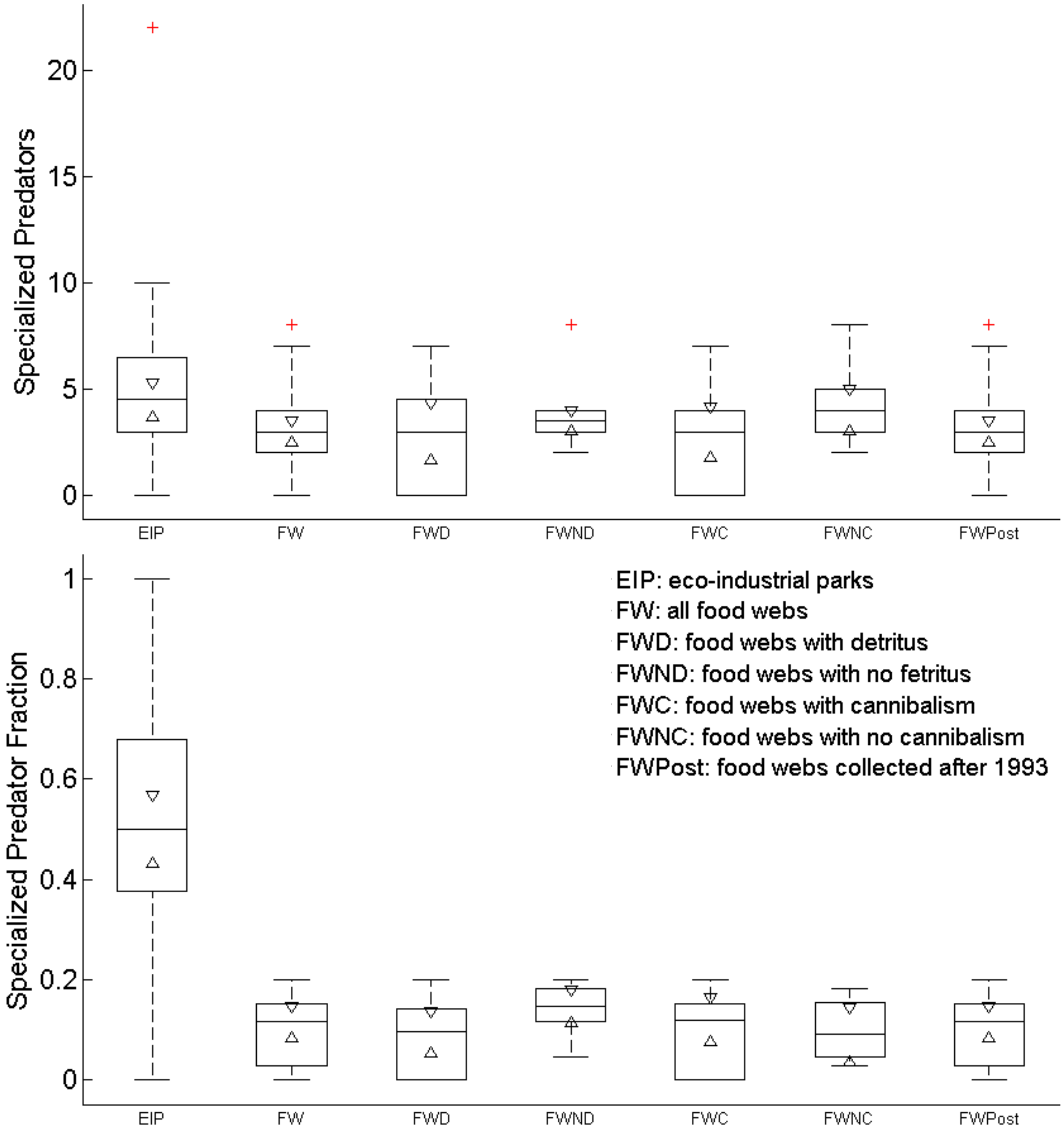


Figure 22-1: Two ecosystem metrics calculated from the food web matrix [**F**] as applied to Eco-Industrial Parks (EIP) and Food Webs (FWA) datasets. The food web dataset (*FWA*) is then organized into those with a documented detritivores component (*FWD*), a documented cannibalism interaction (*FWC*), those without (*FWND* and *FWNC* respectively), and those food webs collected after 1993 (*FWPost*). *Note*: There was no data regarding the two metrics investigated here for those food webs collected before 1993. The line drawn within the box is the median, and box is represents 25th and 75th percentiles, with the tick marks representing the inter-quartile range, crosses show outliers and triangles depict confidence limits.

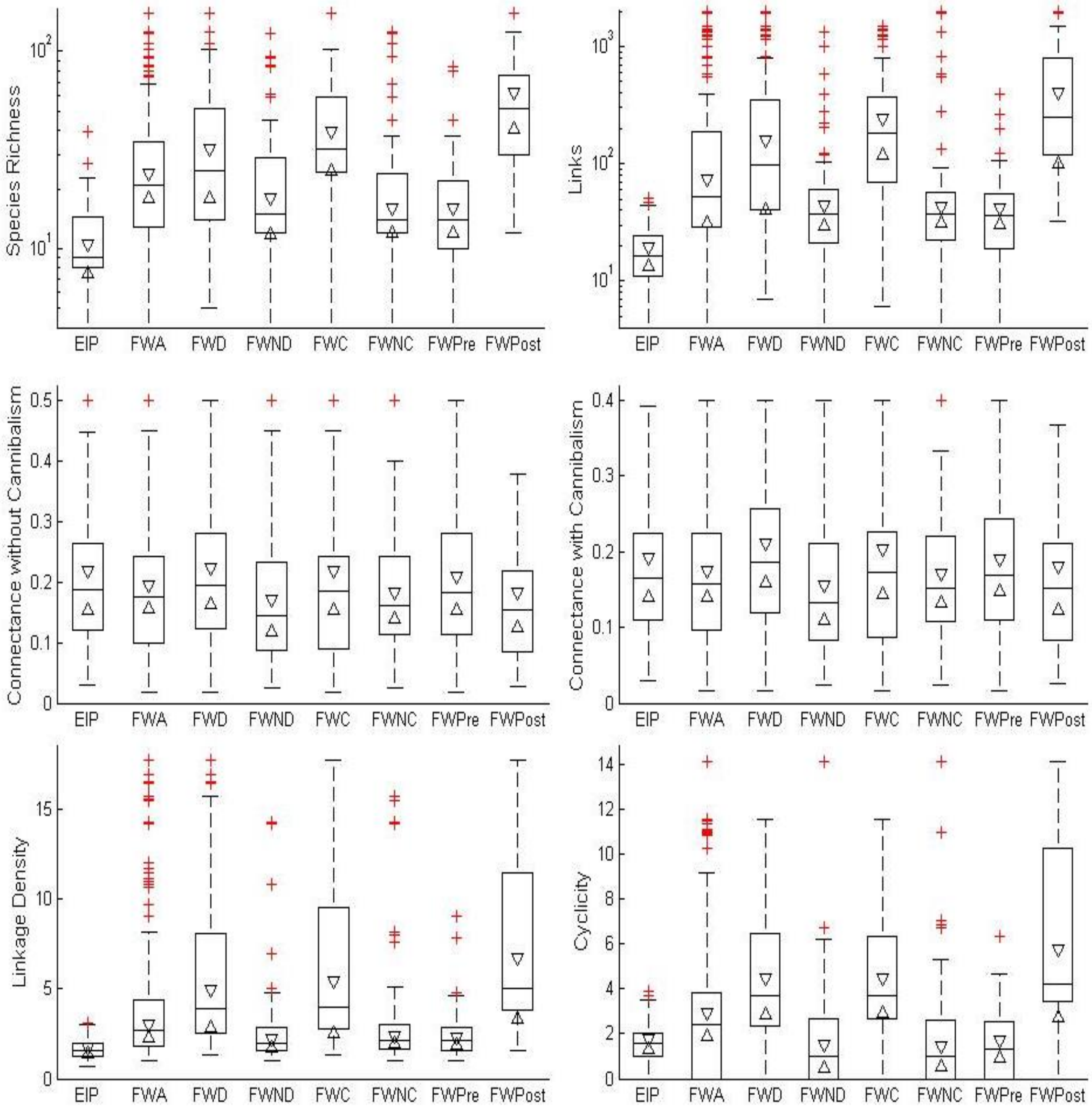


Figure 22-2: Five ecosystem metrics (with a variation on one) calculated from the food web matrix [**F**] as applied to Eco-Industrial Parks (*EIP*) and Food Webs (*FWA*) datasets. The food web dataset (*FWA*) is then organized into those with a documented detritivores component (*FWD*), a documented cannibalism interaction (*FWC*), those without (*FWND* and *FWNC* respectively), and those food webs collected prior to 1993 (*FWPre*) and after 1993 (*FWPost*). The line drawn within the box is the median, and box is represents 25th and 75th percentiles, with the tick marks representing the inter-quartile range, crosses show outliers and triangles depict confidence limits.

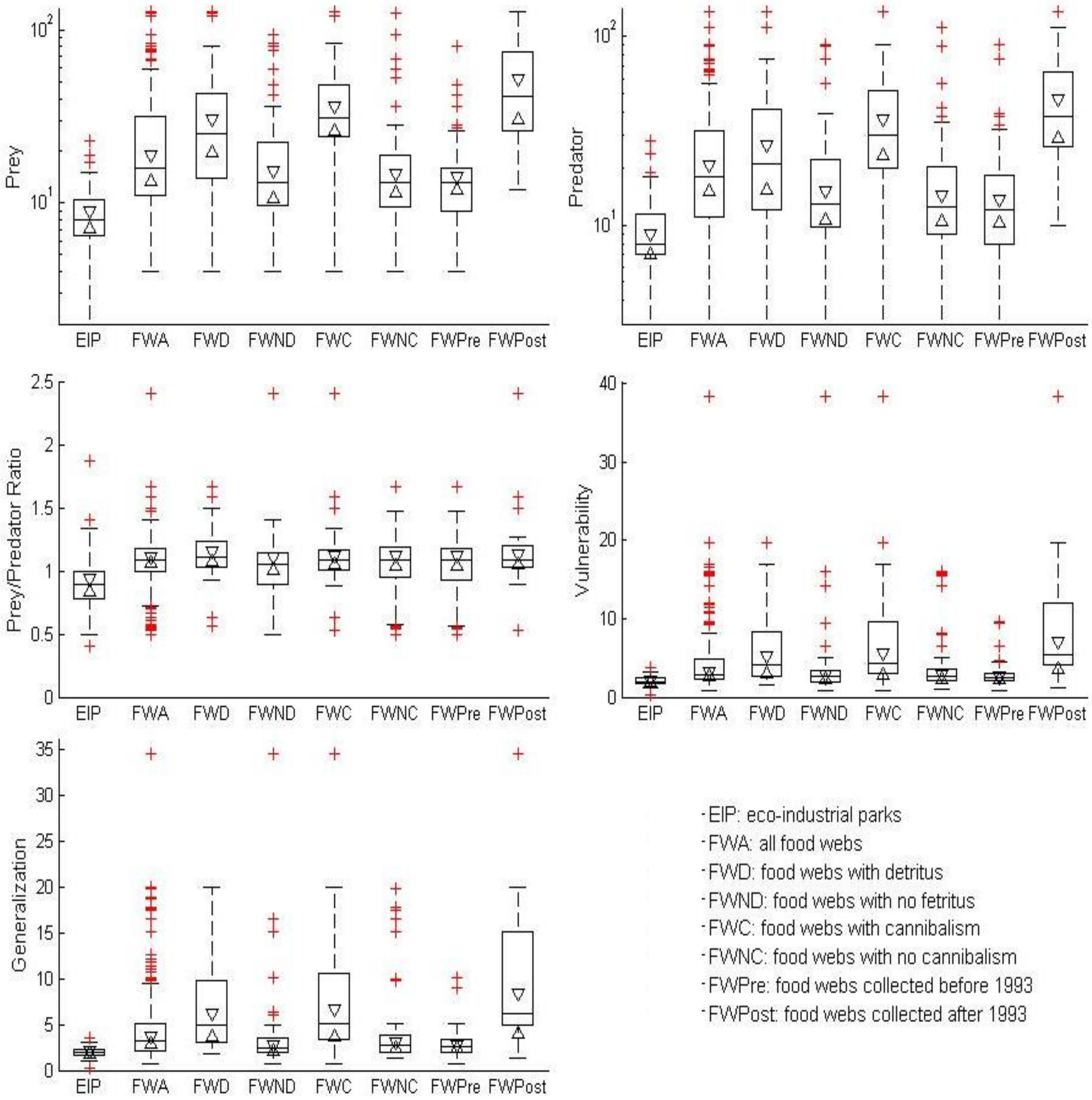


Figure 22-3: Five ecosystem metrics calculated from the food web matrix [**F**] as applied to Eco-Industrial Parks (*EIP*) and Food Webs (*FWA*) datasets. The food web dataset (*FWA*) is then organized into those with a documented detritivores component (*FWD*), a documented cannibalism interaction (*FWC*), those without (*FWND* and *FWNC* respectively), and those food webs collected prior to 1993 (*FWPre*) and after 1993 (*FWPost*). The line drawn within the box is the median, and box is represents 25th and 75th percentiles, with the tick marks representing the inter-quartile range, crosses show outliers and triangles depict confidence limits.

Table 9: Summary of Figure 22. Medians and notch intervals for twelve food web metrics as applied to EIP and FW datasets. If the notch intervals do not overlap then the median of the two datasets may be said to be statistically different at the 5% significance level.

| Metric | Dataset | Median | Notch Interval | Statistically Different at 5% Significance Level? |
|---|---|---|---|---|
| **Species Richness** | *EIP* | 9 | [ 7.53 , 10.5 ] | Yes |
| | *FW All* | 21 | [ 18.3 , 23.9 ] | |
| **Links** | *EIP* | 17 | [ 13.4 , 19.6 ] | Yes |
| | *FW All* | 52 | [ 31.1 , 72.9 ] | |
| **Linkage Density** | *EIP* | 1.55 | [ 1.39 , 1.71 ] | Yes |
| | *FW All* | 2.67 | [ 2.32 , 3.01 ] | |
| **Connectance with Cannibalism** | *EIP* | 0.166 | [ 0.140 , 0.192 ] | No |
| | *FW All* | 0.158 | [ 0.141 , 0.174 ] | |
| **Connectance without Cannibalism** | *EIP* | 0.186 | [ 0.154 , 0.219 ] | No |
| | *FW All* | 0.175 | [ 0.156 , 0.193 ] | |
| **Prey** | *EIP* | 8 | [ 7.09 , 8.91 ] | Yes |
| | *FW All* | 16 | [ 13.3 , 18.7 ] | |
| **Predators** | *EIP* | 8 | [ 6.98 , 9.02 ] | Yes |
| | *FW All* | 18 | [ 15.3 , 20.7 ] | |
| **Specialized Predators** | *EIP* | 5 | [ 3.71 , 5.29 ] | Yes |
| | *FW All* | 3 | [ 2.49 , 3.51 ] | |
| **Prey-Predator Ratio** | *EIP* | 0.882 | [ 0.838 , 0.940 ] | Yes |
| | *FW All* | 1.08 | [ 1.06 , 1.11 ] | |
| **Specialized Predator Fraction** | *EIP* | 0.500 | [ 0.431 , 0.569 ] | Yes |
| | *FW All* | 0.115 | [ 0.084 , 0.146 ] | |
| **Vulnerability** | *EIP* | 2 | [ 1.84 , 2.16 ] | Yes |
| | *FW All* | 2.92 | [ 2.59 , 3.25 ] | |
| **Generalization** | *EIP* | 1.96 | [ 1.77 , 2.07 ] | Yes |
| | *FW All* | 3.27 | [ 2.89 , 3.66 ] | |
| **Cyclicity** | *EIP* | 1.56 | [ 1.33 , 1.79 ] | Yes |
| | *FW All* | 2.41 | [ 1.91 , 2.92 ] | |

## 5.4 Discussion: General Patterns and Comparisons

Figure 22 shows trends across 10 food web metrics for food webs and EIPs. Statistical comparisons between the two networks types are summarized in Table 9. The results indicate that EIPs and ecological food webs differ among a number of metrics that describe form and structural patterns. Median values for the EIPs vs. Food Webs (EIP vs. FW All in Figure 22) can be said to be statistically different with 95% confidence for the metrics species number, links, linkage density, prey, predators, prey-predator ratio, vulnerability, and generalization (summarized in Table 9). The differences highlight that the structure of EIPs and food webs are dissimilar, which translates into differences in network functions. Also seen here is that structural metrics are sensitive to the types of interactions represented (here specifically cannibalism and detritivores). It follows that other metrics not investigated here may also be affected by the types of interactions represented in a system.

EIPs in comparison with food webs were found to be smaller networks with a lower density of connections ($N$, $L$, $L_D$). The number of species and links define the network, while the density of these linkages and their ratio to number of connections structurally possible define the structure. The lower degree of connectivity in EIPs translates, as expected, to lower numbers of prey and predators composing the system ($n_{prey}$, $n_{predator}$). The density of linkages per prey ($V$) and predators ($G$) in the system, 40-70% lower in EIPs than food webs, tells us each predator in an EIP exploits less prey ($G$), and prey are consumed by fewer predators ($V$). The ratio of prey to predators ($P_R$) in EIPs is about 20% lower than that in natural food webs. The lower densities of linkages, prey, and predators indicate that each component in an EIP transfers material to and from, a smaller number of components than in a food web.

### 5.4.1 Differences between Food Web and Industry Behavior

The goal of the analogy between industry and nature is to build a model by transferring the knowledge of ecosystems to explain behaviors of the industry systems. There are many obvious commonalities between the two systems: both are complex systems made up of interacting components that transform the materials and energy flowing between them and this flow is regulated by things such as competition and mutualism. Both systems undergo continuous changes and have reached their present state through an evolutionary process of one form or another. A truly useful model must understand the dissimilarities as well. Knowing the gaps in an analogy is necessary however no analogy is perfect: some concessions must be made for the sake of the knowledge to be gained, a point that is sometimes missed in the literature. There have been numerous papers discussing the faults of the analogy between ecosystems and industrial networks. Levine points out that all industrial relationships stem from the importance of products, and a demand for products is what drives the system (Levine 2003). This is in contrast with the input driven ecosystem where production is limited by the available energy. The production limits in industry are, relative to nature, a non-issue. One of the goals of sustainable design is to limit production to the reusable resources available and using nature as a model, a system that already has this structure in place, can aid in this goal. Graedel points out the stark contrast between the amounts of resources taken from outside the system in industry as opposed to in an ecosystem as a result of the subpar ability of industry to use all available material and energy (Graedel 1996).

One behaviors of food webs is the dependence of pathway proliferation rate (measured by cyclicity – representative of cycling in the system) on the number of species/actors/nodes in the system (Borrett and Patten 2003). The set of food webs collected in this dissertation is investigated for this property; see Figure 23(c). A strong trend is not visible for the food webs. One explanation is the set of food webs used here is possibly too small for this property to emerge. The same trend is investigated for the EIPs collected here; see Figure 23(a). The pathway proliferation rate appears to have very little if no relation to the size of the industrial system. Figure 23(b) and (d) investigate the dependence on the number of links in the system. Both show a slightly higher tendency for pathway proliferation rate to increase with the number of links in the system; however the relationship is still a very weak one. The slight correlation with the number of links in the system is expected, the more linkages there are the more opportunities there are available for cycling in the system, however an increased existence of linkages does nothing to ensure that the cycling will be higher.

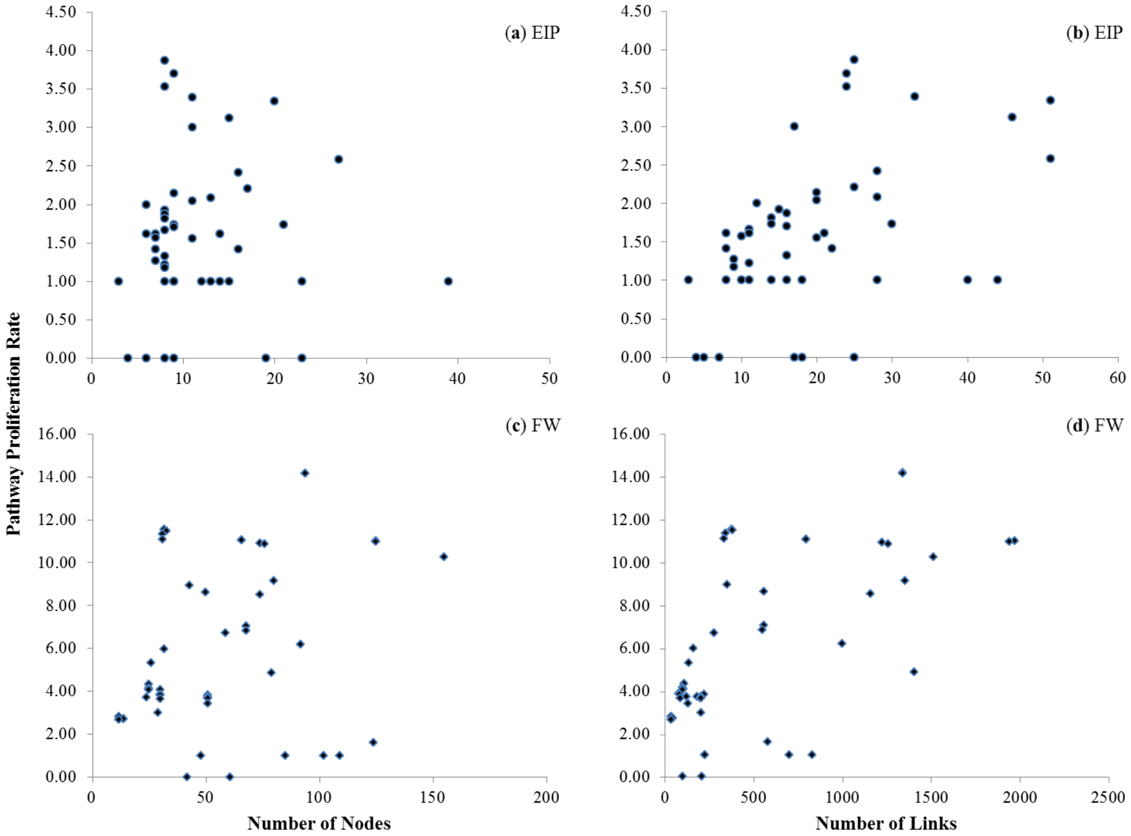


Figure 23: An attempt to confirm or deny the suspected dependence of the systems pathway proliferation rate (measured using cyclicity) on number of nodes (left plots) and links (right plots). (a) and (b) at the top left and right, cover the 48 EIPs, while (c) and (d) on the bottom left and right, cover the food webs collected post 1993.

The conclusions drawn from Figure 23 reassure that any correlation found with regards to pathway proliferation rate, or cyclicity, is not simply an artifact of system size. This is an important finding as the majority of the EIPs in the collection here are made up of less than 30 actors, while the food webs collected here cover a much broader range: from 4 to 155 (see Figure 24). The medians of the two groups (*EIP* and $FW_{All}$) are statistically different, as well as the medians of the *EIP* as compared to all other subgroups of the food webs.

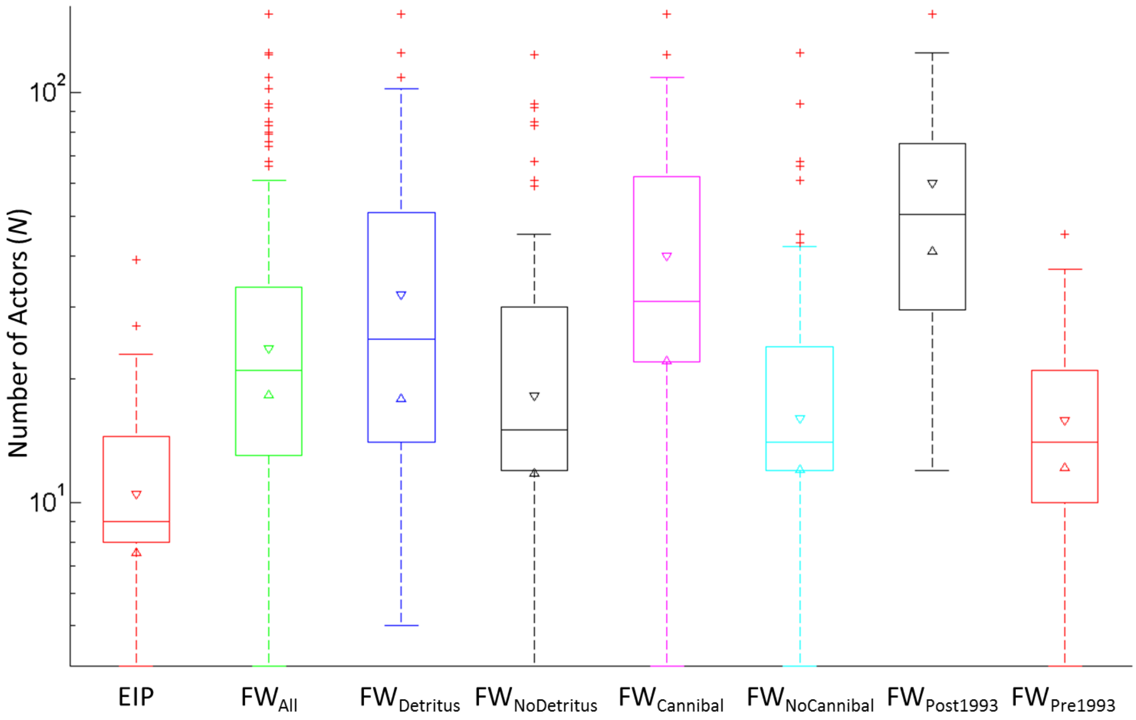


Figure 24: System size for the eco-industrial park (*EIP*) dataset as compared to the food web datasets ($FW_{All}$ representing all food webs in the set, the rest are subgroups thereof), showing the disparity in the number of actors between the two system types.

### 5.4.2 Cyclicity and the Detritus Actor

Cyclicity, a measure of internal cycling often found in networks as some form of recycling, is a measure of efficient materials and energy use in the system. As energy and materials savings in EIPs are highly dependent on the successful cycling of waste and byproducts, cyclicity is an important metric. Differences in the metric cyclicity, with the median value for EIPs falling 55% below that of food webs, highlight the less complex internal cycling present in the structure of EIPs as compared food webs. Median cyclicity values for both networks are greater than or equal to one, meaning that internal cycling is present in both EIPs and FWs. The median value of cyclicity for food webs however is more than one and a half times larger than EIPs, indicating food webs have developed a much more complex set of pathways on average. While many EIPs fall into the category of having a cyclicity equal to one, indicative of having at least one single cyclic loop that all connected components participate in, a number of the EIPs show a cyclicity of zero, meaning no cyclic structure is present in the system. This is essentially a failure on the part of the EIP designers to mimic the structure and function of food webs.

High cyclicity values (>>1) relate strongly to the overall proportion of the energy retained or used within the system vs. that which is lost or discarded by the system. This relationship is reflected in the analysis done on thermodynamic power systems in chapter 4. The results of that analysis suggest that designing EIPs with a high cyclicity structure may lead to more efficient closed-loop industrial networks. Despite consumer and financial support, recycling in industrial systems still only accounts for a small fraction of mobilized matter. Most recycling is in the form of metals collected and shipped to an offsite recycling facility (2008). The potential for onsite reuse of water and other byproducts is immense and much better reflects the role of the detritivores in an ecosystem.

The internal cycling in food webs is very strongly influenced by the presence of recyclers. An ecological recycling component is often indicated by ‘detritus’ or ‘decomposers’ being listed amongst the species, as well as cannibalism, which creates a self-loop. These specialized interactions were previously dismissed by food web theorists; a lack of documented cannibalism and decomposers was detailed as one of the four substantial problems in food web ecology prior to the early 1990’s (Polis 1991, Cohen, Beaver et al. 1993). Changes in collection and documentation techniques since 1993 have resulted in a greater percentage of food webs documenting detrital and cannibalistic links (in the dataset used here: 92% after 1993 vs. 26% before). The documentation of the specialized interactions of detritivores and cannibalism is likely the reason behind the large differences in median values of structural parameters ($N$, $L$, $L_D$, $n_{prey}$, $n_{predator}$, $V$, $G$) in food webs collected before and after 1993.

A comparison of the cyclicity values shows that EIPs generally appear to be less connected than natural food webs. The types of interactions present (cannibalism, decomposers, competition, etc.) influence the magnitude of these differences; EIPs fall closer to those food webs without cannibalism and detrital interactions, suggesting that the failure to include such functional roles in EIPs is at least partially responsible for their lower cyclicity relative to food webs.

Due to the ecological importance of the decomposer/detritus functional group a detritus-type actor within an EIP is defined here and the frequency of their occurrence in an EIP is quantified. A detritus-type actor for an EIP is here defined as an actor which is of the type waste treatment (including composting), recovery and recycling (including repair, remanufacture, reuse, resale), or agriculture (including farm, zoo, landscaping, green house, golf course). The actor also needed to have at least one connection entering and leaving it in order to qualify as a detritus-type actor. This last criterion is based on the fundamental job description of a detritus/decomposer in a food web and ensures that the detritus-type actor is an active participant of the system. The number of active detritus is plotted against the cyclicity of all 48 EIPs in Figure 25. The plot area between zero and one on the x-axis is greyed out as the value of cyclicity cannot fall between these two limits.

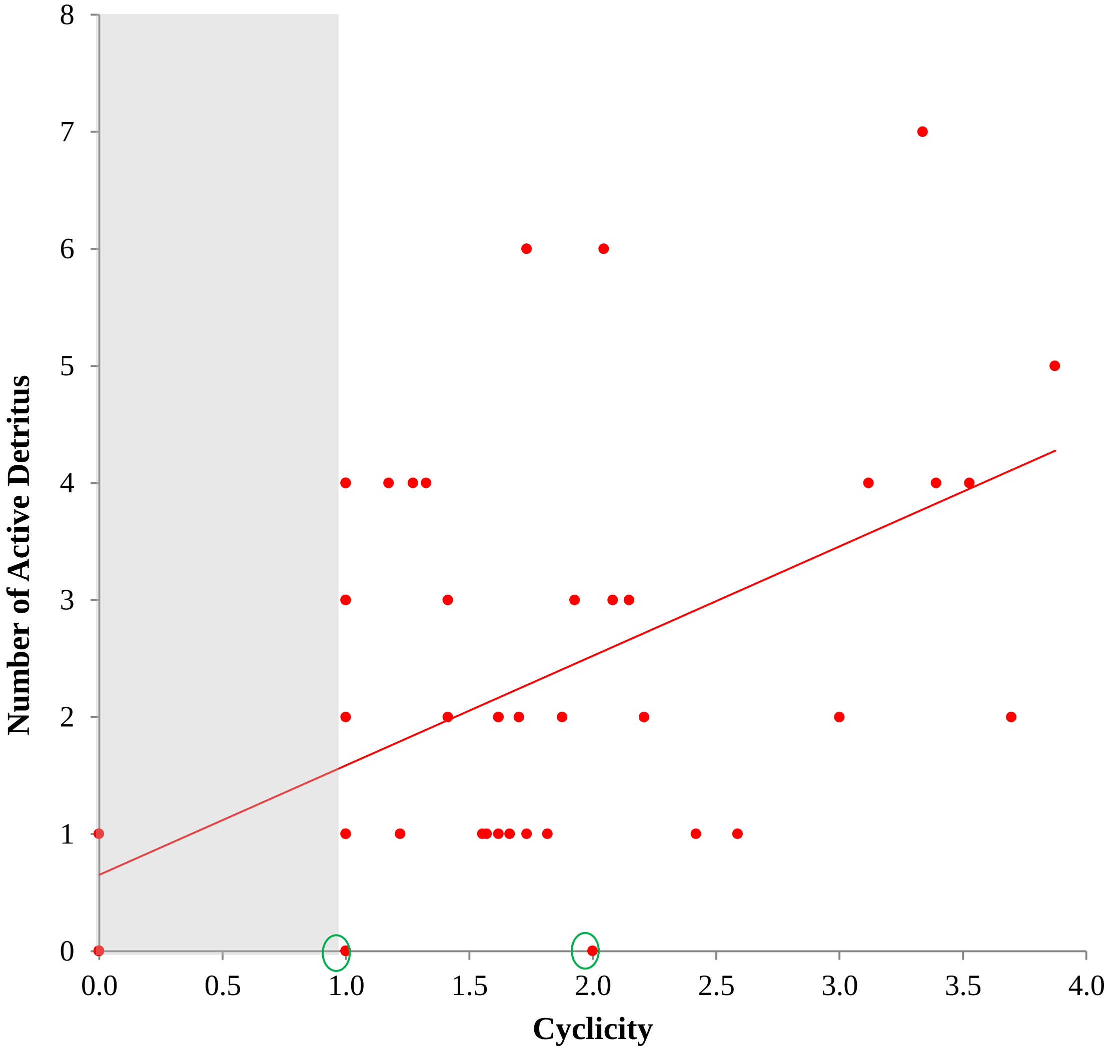


Figure 25: The number of active detritus in an EIP as determined by the cyclicity of the network. The two data points circled both have no active detrital actors but still have a greater than zero cyclicity, Harjavalta with a cyclicity of 2.0 and the Lower Mississippi Corridor with a cyclicity of 1.0, are looked into in the text that follows.

To address some of the outliers: the EIP represented as having no active detritus and yet a cyclicity value of 2, relatively high for what would be expected of a network with no recycling component, is the Harjavalta industrial area in Finland. Looking further into this EIP we find that the full industrial park does include a wastewater treatment plant and an industrial cleaning facility. These two companies are not included in the material and energy exchange diagram provided in the literature (Heino and Koskenkari 2004, Saikku 2006, Heino 2012). The existence of a detrital-type actor cannot be discounted as being a contributor to the success of this EIP as the wastewater treatment plant and cleaning facility may contribute behind the scenes to the overall structure. The material and energy exchanges between firms in the industrial network as documented in the literature are shown in Figure 26. Although none of the companies within the network fall into the functional categories defined above for a detritus-type actor, they do all meet the active participant requirement, with five of the six actors having at least one connection entering and leaving. This is why the cyclicity is so high.

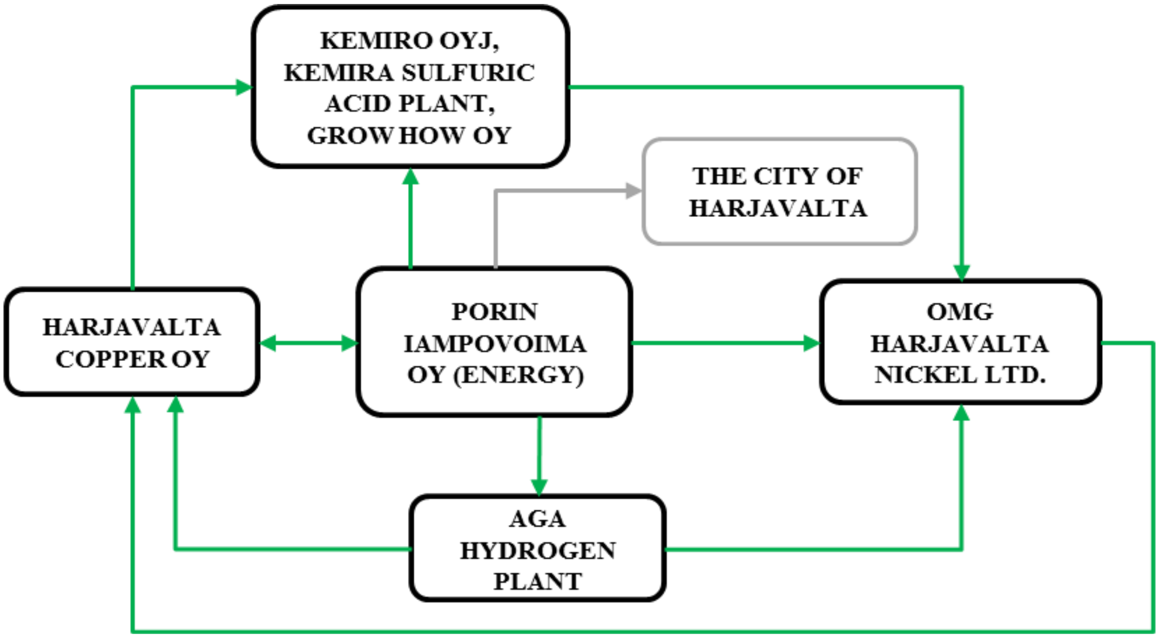


Figure 26: The Harjavalta industrial area in Finland. Green linkages indicate connections which participate in a cycle, grey linkages do not. Greyed boxes indicate an actor which exclusively participates in incoming or outgoing interactions (is only a predator or prey). *Figure adapted from* (Heino and Koskenkari 2004).

The outlier in Figure 25 with a cyclicity of one but no active detritus is the Lower Mississippi Corridor. This EIP falls into the same situation as the Harjavalta industrial area: there is no detritus-type actor as defined. Figure 27 gives a visual description of the material and energy exchanges between firms showing that the cyclicity of the Lower Mississippi Corridor results from three bi-directional links between three different pairs of actors. Technically a bi-directional link (or two actors linked in both directions) does create a cycle however it is not the complex cycling of ecosystems that EIPs strive to mimic.

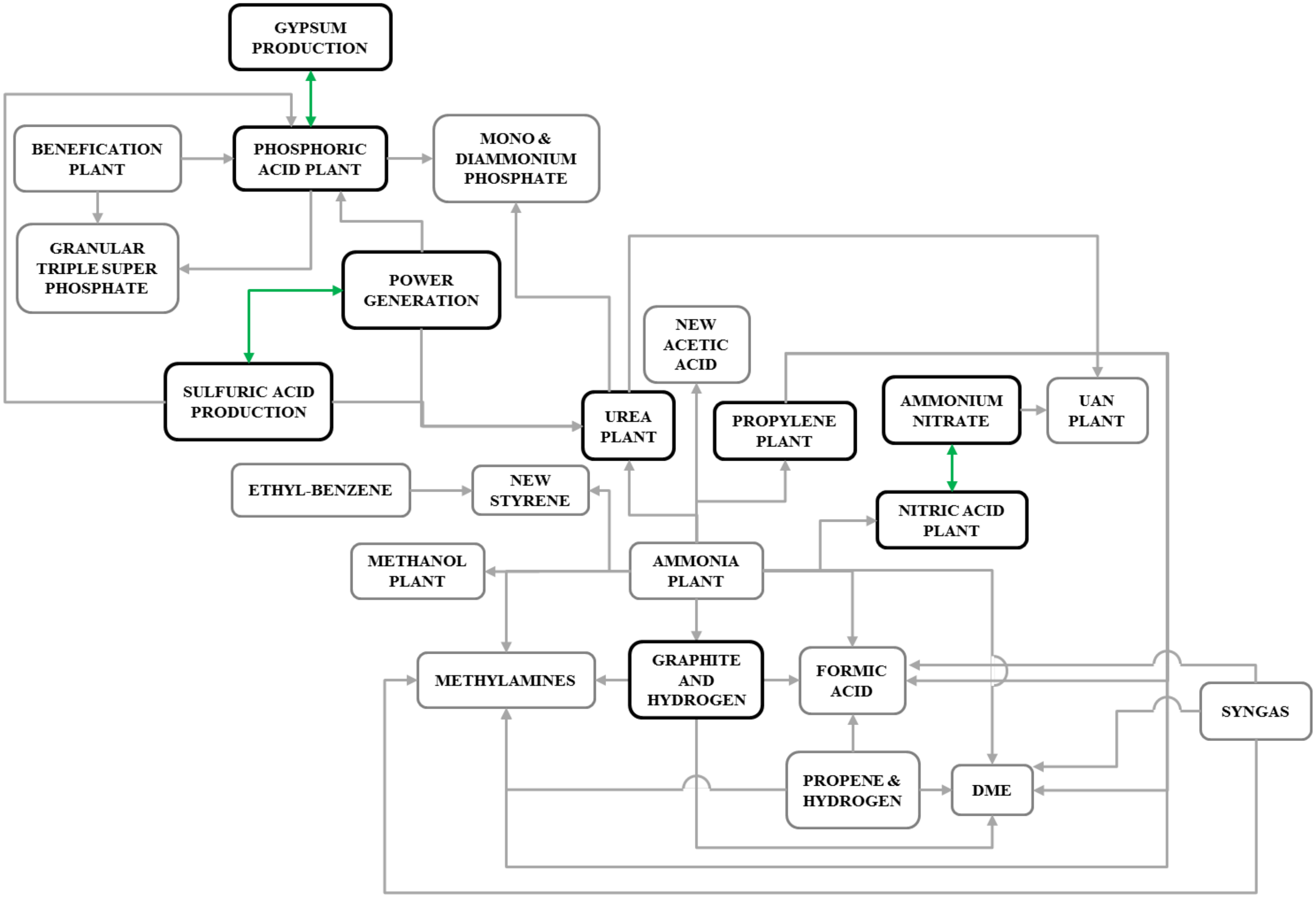


Figure 27: The Lower Mississippi Corridor EIP. Green linkages indicate connections which participate in a cycle, grey linkages do not. Greyed boxes indicate an actor which exclusively participates in incoming or outgoing interactions (is only a predator or predator or prey). *Adapted from* (Xu, Indala et al. 2005, Singh, Lou et al. 2007).

### 5.4.3 The Presence of Exclusive Actors

Figure 28 shows that most of the actors in the Lower Mississippi Corridor exclusively participate in incoming or outgoing interactions, as represented by a grey box surrounding the name of the actor. An exclusive actor is defined here as an actor that only acts as predator or only prey, or only consumes or produces materials and energy. The result is that an exclusive actor does not contribute to building a cyclic system. In an ecosystem for which system boundaries could be drawn to perfectly encompass the entire system, all actors at some point would be both a predator and a prey. Even the top predators in such an ecosystem, which have no natural predators, are at some point through death are consumed by detritus and decomposers. In reality however the system boundaries are not always ideally selected and due to error on the part of the collector certain relationships can be missed. The resultant food web would then document some exclusive actors. The abundance of exclusive predators and prey in some EIPs limit their ability to mimic the performance of food webs, which generally have fewer exclusive actors. Figure 28 and Figure 29 show the extent that the 48 collected EIPs are composed of exclusive actors. The blue diamonds in each plot represent the food webs from the post-1993 dataset for comparison.

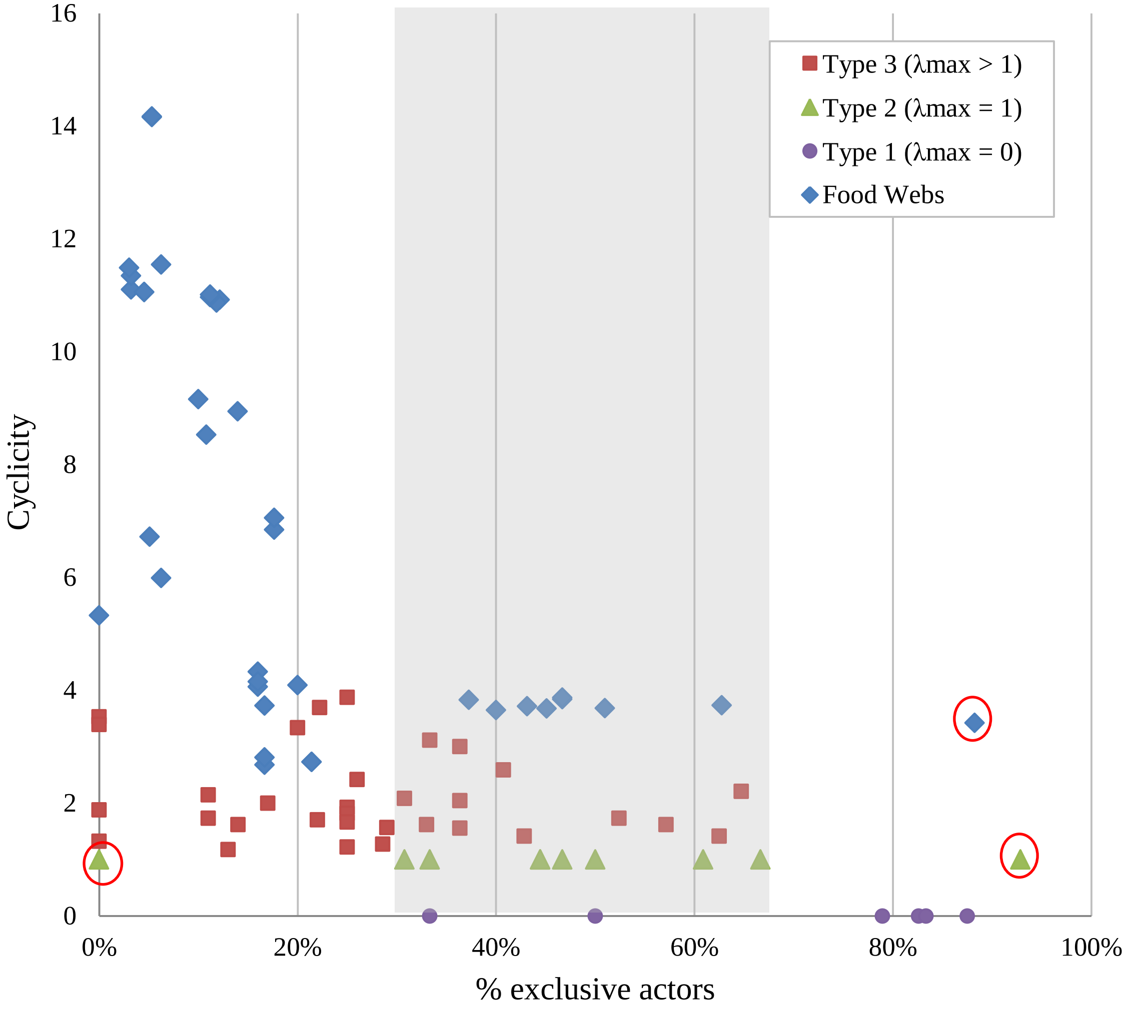


Figure 28: The relationship between cyclicity and actors in an EIP or FW which are exclusively prey or predator. The x-axis represents the percentage of total actors in an EIP or FW that acts exclusively as a prey or predator, or only provides or receives respectively materials and energy.

Figure 28 looks at the percentage of actors in an EIP that are exclusive, either prey or predator. Figure 28 suggests that an EIP that has more than 70% of actors in an exclusive role is severely limited in its ability to have any amount of internal cycling. The food webs with the highest cyclicities are made up of less than 20% exclusive actors. Overall, with the exception of one outlier, the percent of total system actors that are exclusive in food webs stays below 65%, which is not much different from the upper limit seen for the EIPs.

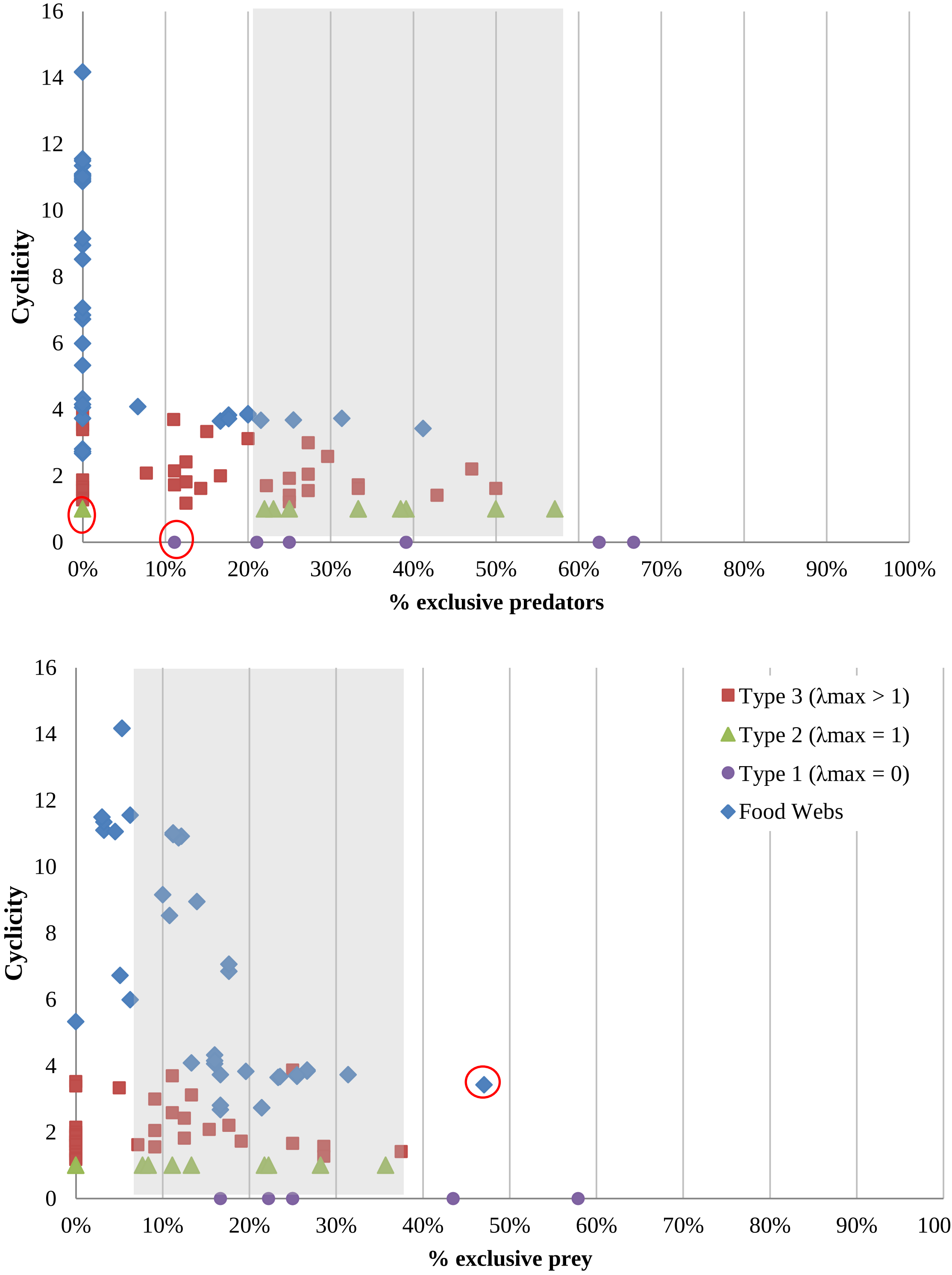


Figure 29: The relationship between cyclicity and the percentage of actors which are exclusively predators (top plot) and prey (bottom plot). The x-axis represents the percentage of total actors in an EIP or FW that acts exclusively as predator (top figure) or a prey (bottom figure), or only provides or receives respectively materials and energy.

Figure 29 separates the EIP actors into those who function in an exclusively predatorial-type role or exclusively prey type role. Figure 29-top relates cyclicity to the percentage total actors in the network that are exclusively predators. These actors only interact with other companies by accepting inputs and have no relationships based on outputs to other companies. Figure 29 -bottom relates cyclicity to the opposite, the percentage of total actors in the network that are exclusively prey. These actors only interact by providing a good or service to another company, they do not have any relationships based upon inputs received from other companies. So while Figure 28 shows a possible upper bound of 70% for observed exclusive EIP actors that still allow for a structure with internal cycling, Figure 29 shows possible upper bounds for internal cycling in an EIP as:

- In an EIP fewer than 60% of observed actors may be exclusively predator.
- In an EIP fewer than 40% of observed actors may be exclusively prey.

The food webs plotted in Figure 29 show bounds of:

- In a FW the percent observed exclusive predators for food webs falls below 45%.
- In a FW the percent observed exclusive prey falls below 35% (with one outlier).

Those food webs with the highest cyclicity had an even lower upper bound, especially for the percentage exclusive predators. Those food webs with cyclicity greater than 4.0 had **no** observed/documented exclusive predators in the system. The same food webs did have some percentage of exclusive prey in the system but the upper bound was still lower at less than 20%. There was only one food web in the dataset that did not contain any exclusive prey. The relatively low upper bound for the exclusive prey is interesting and perhaps suggestive of a guide for EIP designers if the bound holds for other measures of EIP success.

One explanation for the trends in Figure 28 and Figure 29 is that the system boundaries of an EIP are not analogous to the system boundaries of a food web. The EIPs collected here only document operational flows: water, electricity, materials, etc. They do not document structural flows, such as the flows of machinery or building and warehouse structures. Where does a tractor go when it is no longer functional? What happens to a building when it becomes too old to use and is abandoned? How is a company that is bought out by another company accounted for in the analogy? These questions all reduce to questions of how to account for structural decay in an EIP. Do the boundaries of an EIP need to be extended? This presents an issue for researchers using pre-collected data, the way that EIP data is reported cannot be easily influenced. Does there need to be a maintenance actor included in the boundaries of all EIPs?

There is the possibility that the inclusion of this information would better mimic the structural decomposition occurring in a food web. Structural flows in a food web are averaged into the population. One species in a food web is made up of enough individuals that were a single individual to die and be physically decomposed this process can be averaged such that the interaction between dead individual and decomposer is always present. The population of any species is large enough that it is assumed that this connection occurs on a regular basis.

The benefit of large population sizes for each species has not been translated to EIPs. When each company is a species (the analogy as currently used) a population of one is created for each species. The process of structures passing out of operation in EIPs occurs on a temporal time frame with this species definition. This presents a different problem from the essentially steady state time frame of operational interactions in an EIP and what is used to describe food webs. This leads to the question: are structural flows necessary for an accurate food web analysis of EIPs? The value of flow based information to a food web analysis of EIPs is tested later in chapters 8 and 9.

### 5.4.4 System Size: Number of Actors

Table 10: Summary of Ecological Food Web Observations

| **No variance with Food Web Size ($N$):** | | |
|---|---|---|
| | The maximum chain length is short (approximately 3-4 links) | Disproved (Pimm, Lawton et al. 1991) |
| | Prey to predator ratio ($P_r$): remains a constant at approximately 1 (0.8819) (Cohen 1977) | Disproved (Pimm, Lawton et al. 1991) |
| | Linkage density ($L_d$) is on average constant or increasing in proportion to the number of species: or that the relationship between $L$ and $N$ in a food web is linear (Cohen, Briand et al. 1990) | Disproved (Pimm, Lawton et al. 1991, Havens 1992) |
| | Generalization ($G$) does not vary with food web size ($N$) (Schoener 1989) | |
| **Other relationships with Food Web Size ($N$):** | | |
| | Connectance ($c$) is constant. (Warren 1990, Martinez 1992, Pimm 2002) | |
| | Vulnerability ($V$) increases with food web size ($N$) (Schoener 1989) | |
| | Species number is limited by the number of prey they can consume (Pimm 1982) | |
| | Empirical food webs with $N < 100$ display strong scale dependence. Hypothetical webs with $N > 1000$ display scale invariance (Martinez and Lawton 1995) | |
| | Connectance ($c$) will vary to the degree that specialists, generalists, or omnivores are present (Warren 1990) | |

Although the general relationships in Figure 22 and Table 9 are instructive, ecologists have noted that values of some metrics are clustered or display particular patterns with species number (Cohen 1977, Cohen 1978, Cohen and Briand 1984, Briand and Cohen 1987, Schoener 1989, Warren 1990). These findings are highlighted in Table 10. One of these is that, per equation 11, linkage density ($L_D$) does not vary with species richness ($N$) (Cohen, Briand et al. 1990, Warren 1990), thus we expect a linear relationship between the two. Figure 30 confirms that links increase with species number for food webs (FWA), and also shows that the same can be said for eco-industrial parks (EIP). Linear data fits for the two datasets highlight that the EIPs tend to have significantly fewer links per species than food webs of equal size. The increase of $L$ with $N$ is significantly greater for food webs than for EIPs; the slope for the linear fit of EIP data is 1.4 while for FWA data it is 12, almost 9 times higher. This trend is most apparent at around 30 species, where the relationship of $L$ to $N$ appears to diverge. An ANOVA analysis of $L$ as a function of $N$ with web type as the classification variable confirms these observations; the entire model $R^2$ = 0.73 ($F_3$,187 = 183.7; P <0.001), with significant effects of $N$ (the regression variable), web type, and their interaction ($F_1$,187 = 6.22, $p < 0.001$;  0.054, $F_1$,187 = 1.94, $p = 0.054$; $F_1$,187 = 2.67, $p <$ 0.01; respectively). We cannot comment on the trend between species richness and links seen in Figure 30 beyond $N = 30$ for the EIPs as we only have one EIP example with more than thirty (30) companies.

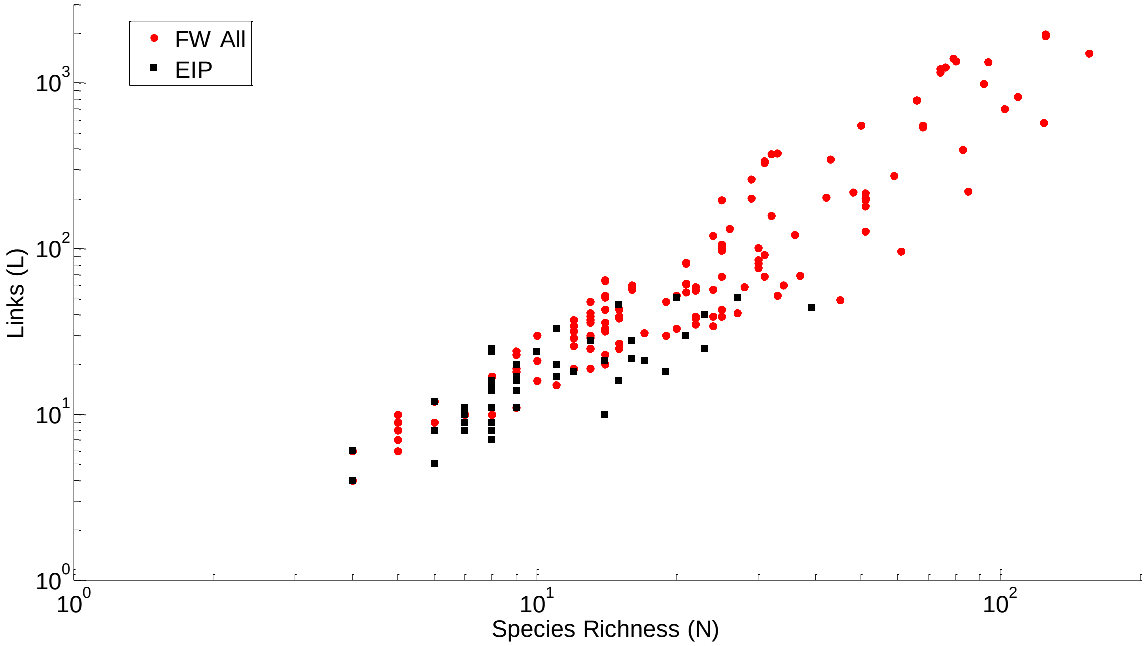


Figure 30: Testing the food web observation that links (L) and species richness (N) are roughly linear on eco-industrial parks (EIP = black squares), as compared to food webs (FWA = red dots). Data on both axes is plotted on a log scale.

Looking at the equations for the structural metrics used here, equations 1-16 in section 3.3.2, shows that some metrics are by definition proportional to food web size ($N$). This would include species ($N$), links ($L$), connectance ($c = L/N^2$), and the number of prey and predators in the system ($n_{prey}$ and $n_{predator}$). Connectance has an extremely strong dependence on the number of species or actors in the system as it is inversely proportional to the square of the system size. Table 11 illustrates the large changes in average connectance values for different groupings of species size for all 144 of the food webs used here as listed in Appendix B. The overall trend is as the networks gets larger or $N$ increases, the connectance gets smaller. This is why it is crucial that if connectance is used as a design metric for EIPs that a goal value is taken from food webs of similar size to the EIP being designed. This is very similar to a method proposed by Bersier, that food webs be grouped according to size to minimize variability due to any size dependence (Bersier and Sugihara

1997). The larger food webs are less numerous in the dataset collected here and therefore their averages are not as strong as the smaller webs (the first 4 sets in Table 11 are the strongest) thus it is not recommended that sets for $N$ = 81-160 (the bottom five) be used as goal values as they currently stand. The rest of the metrics have either been normalized for the size of the food web, as in linkage density ($L_D$), generalization ($G$), vulnerability ($V$), specialized predator fraction ($P_S$), and prey to predator ratio ($P_R$), or they have not been found here to be strongly proportional on the network size – see Figure 23, as in cyclicity ($\lambda_{max}$). When using the first grouping of metrics to make comparisons between EIPs and FWs the focus should be on a dataset of food webs of a similar size to the collected industrial networks, thirty (30) actors or less ($N \leq 30$).

Table 11: For all 144 food webs from Appendix B, average connectance (with cannibalism per equation 11) values for a range of system size ($N$) groupings to show strong fluctuation of connectance with system size.

| **Sets of *N*** | **Number of FWs in set** | **Average Connectance for Set** |
|---|---|---|
| 1-10 | *24* | *0.269* |
| 11-20 | *45* | *0.183* |
| 21-30 | 30 | *0.133* |
| 31-40 | 11 | *0.180* |
| 41-50 | 5 | *0.129* |
| 51-60 | 7 | *0.073* |
| 61-70 | 5 | *0.126* |
| 71-80 | 6 | *0.184* |
| 81-90 | 2 | *0.044* |
| 91-100 | 3 | *0.140* |
| 101-110 | 2 | *0.068* |
| 121-130 | 3 | *0.096* |
| 151-160 | 1 | *0.063* |

Figure 31 and Figure 32 plot the second group of six metrics against the number of actors or species in the system (*N*) to confirm that these six metrics do not directly depend on the size of the network. The $R^2$ values are labeled on the plots for linear trend lines corresponding to each metric. None of the $R^2$ values are high enough to claim a strong dependence on system size, the highest are for the food webs for the metrics generalization, link density, and specialized predator fraction at 0.48, 0.42, and 0.37 respectively. The rest of the $R^2$ values for the food webs, and all of the $R^2$ values for the EIPs, are close to zero.

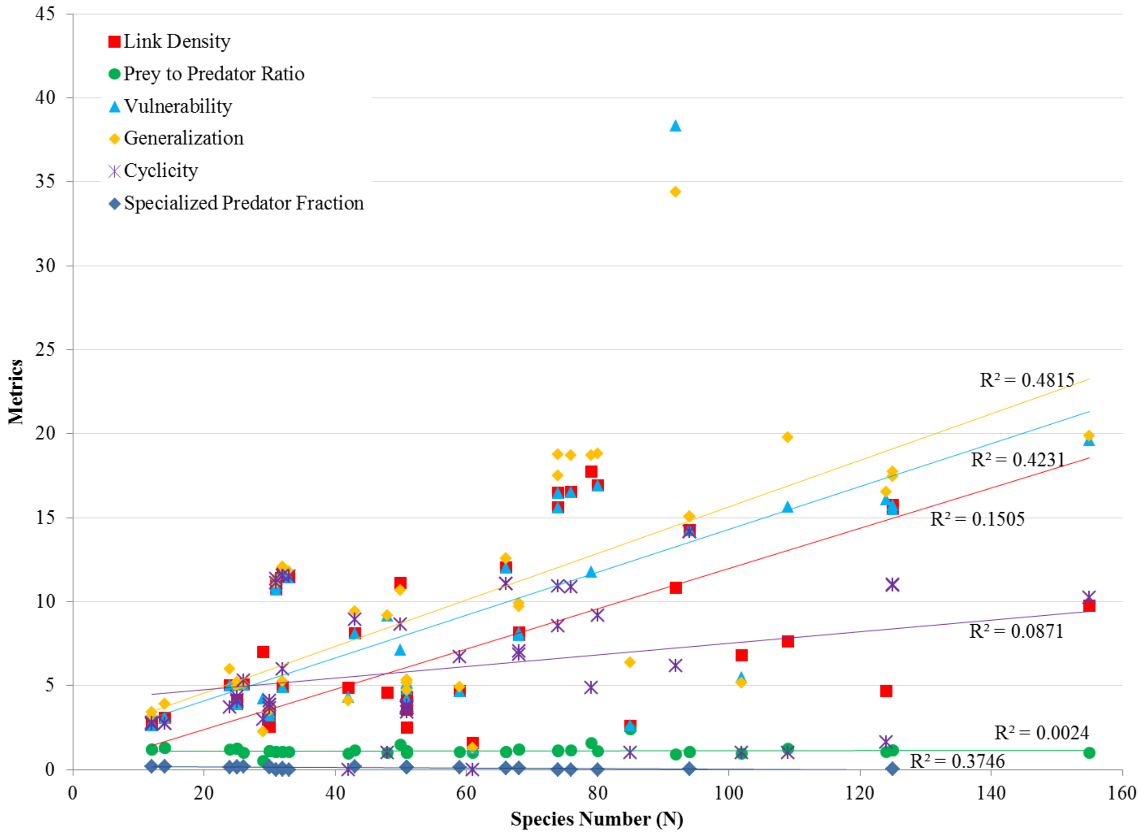


Figure 31: Investigating the proportionality to species number (*N*) for the six metrics chosen: linkage density, prey to predator ratio, specialized predator fraction, vulnerability, generalization, and cyclicity for the Post 1993 Food Webs dataset.

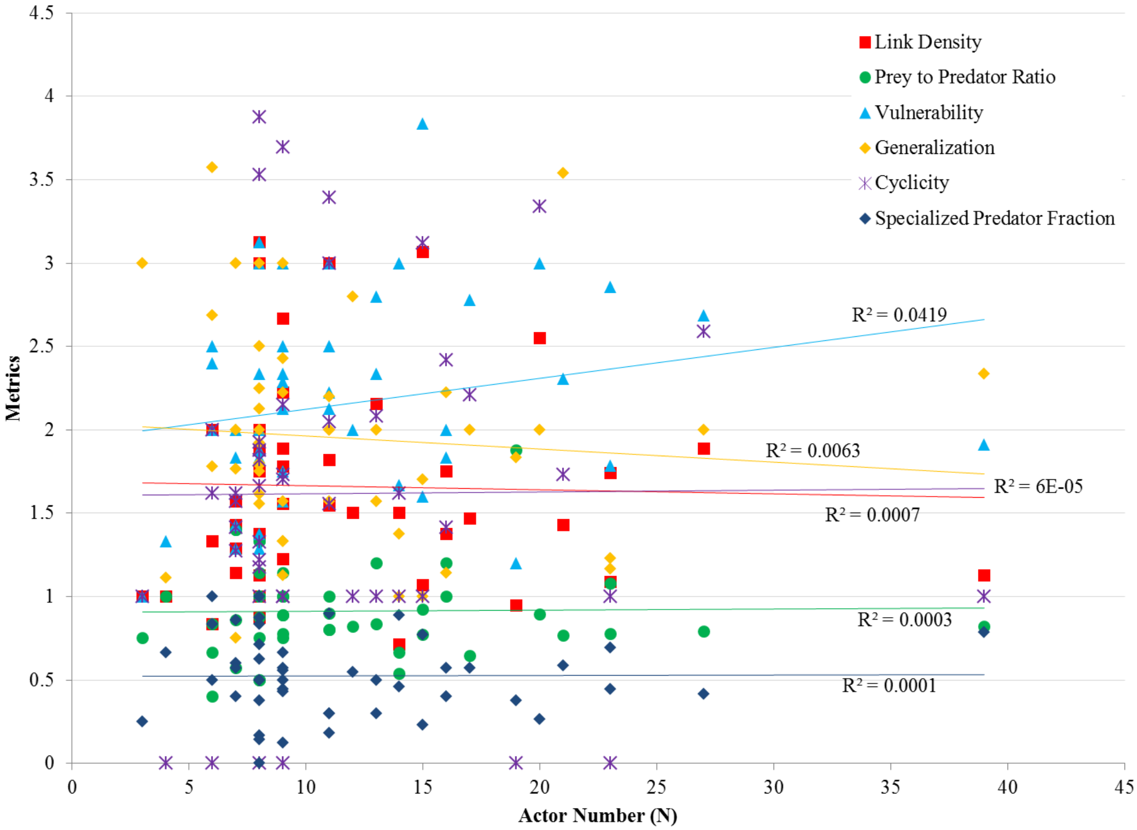


Figure 32: For the Eco-Industrial Parks dataset: investigating the proportionality to actor number (*N*) for the six metrics chosen: linkage density, prey to predator ratio, specialized predator fraction, vulnerability, generalization, and cyclicity.

### 5.4.5 The Agricultural Component: EIP vs IBS

A detritus-type actor for an EIP is partially defined by the dominant type of activities it participated in, specifically as an actor which is of the type waste treatment (including composting), recovery and recycling (including repair, remanufacture, reuse, resale), or agriculture (including farm, zoo, landscaping, green house, golf course). An actor that participates in some type of agriculture is of particular interest in the quest to mimic ecosystems as it is in and of itself a small ecosystem. Does an EIP that contains agriculture automatically behave more like an ecosystem? This is a potentially important question for the designers of EIPs as it could be a quick route to success. The 48 EIPs investigated here were separated into those which had some type of agricultural component and those that did not, 34 of the 48 had an agricultural component and 14 did not.

Figure 33 shows the relationship between linkage density ($L_D$ – open circles and dotted lines) and cyclicity (closed circles and solid lines) between EIPs with (green - IBS) and without (red - EIP) an agricultural component, in terms of the system size (number of actors). IBS stands for ‘integrated bio system.’ Some EIPs are designated an IBS as they have a very dominate agricultural component or characteristic to them. Looking at link density first, it appears that as the network gets bigger the EIPs with an agricultural component have a decrease in linkage density. The EIPs without an agricultural component see an increase in linkage density as the system gets bigger. Thus it appears that for those EIPs without agriculture a larger system will tend to have more links than an EIP with agriculture. One hypothesis is that a network that contains agriculture doesn’t need as many linkages to achieve the same cyclicity.

Cyclicity however shows that both EIP types see a decrease in cyclicity as the system grows. The rate of decrease in cyclicity for EIPs without agriculture is faster than for those with agriculture. The slope of a linear trendline for the cyclicity vs system size of EIPs with agriculture is -0.004, almost steady, while for EIPs without agriculture it is about two and a half times larger at -0.01.

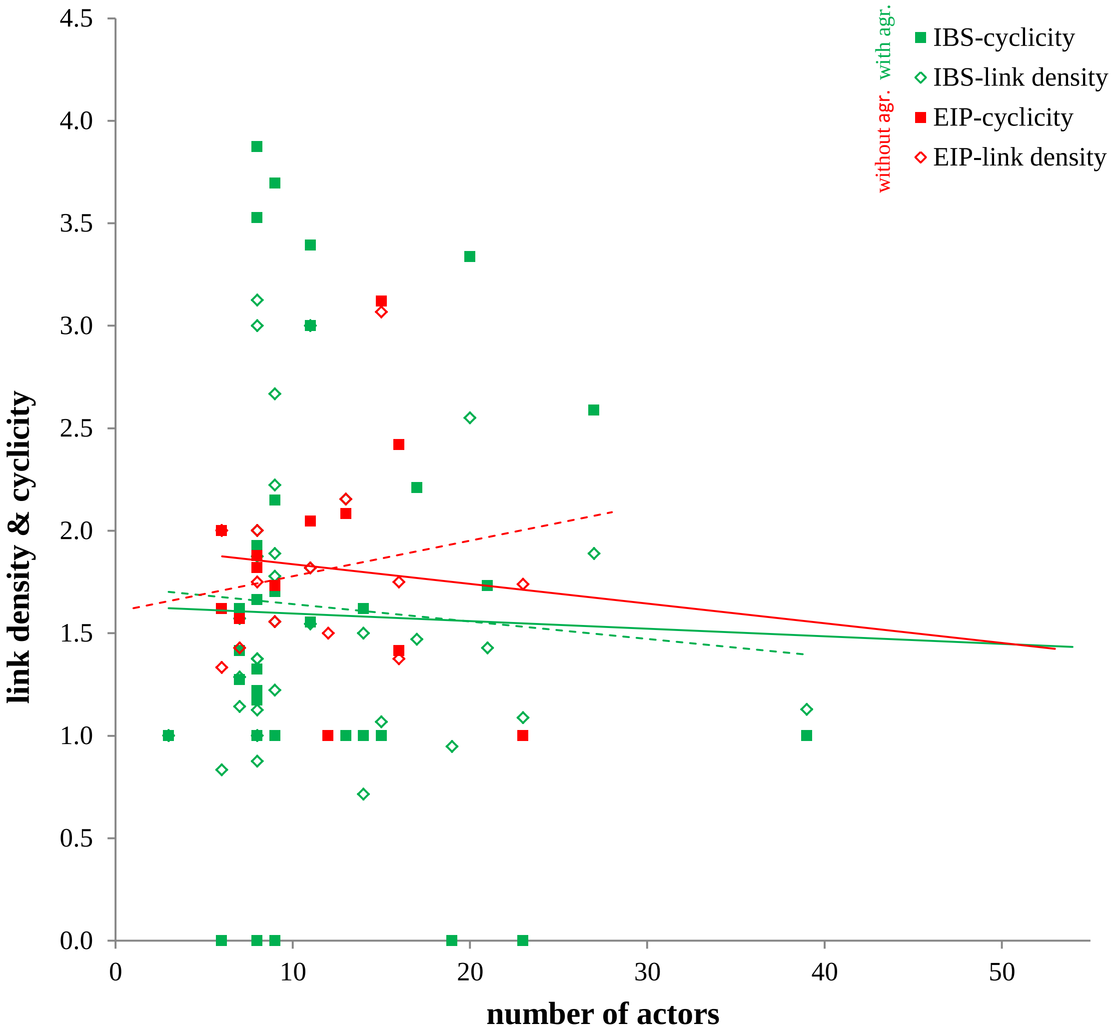


Figure 33: Linkage density (open circles and dotted lines) and cyclicity (closed circles and solid lines) comparisons between EIPs with (green - IBS) and without (red - EIP) an agricultural component, in terms of system size (number of actors).

Figure 34 looks at the effect of the number of active detritus in the system on linkage density and cyclicity in both types of EIPs. As in Figure 33, linkage density is represented by open circles and dotted lines and cyclicity by closed circles and solid lines and EIPs with agriculture are green and without agricultural are red.

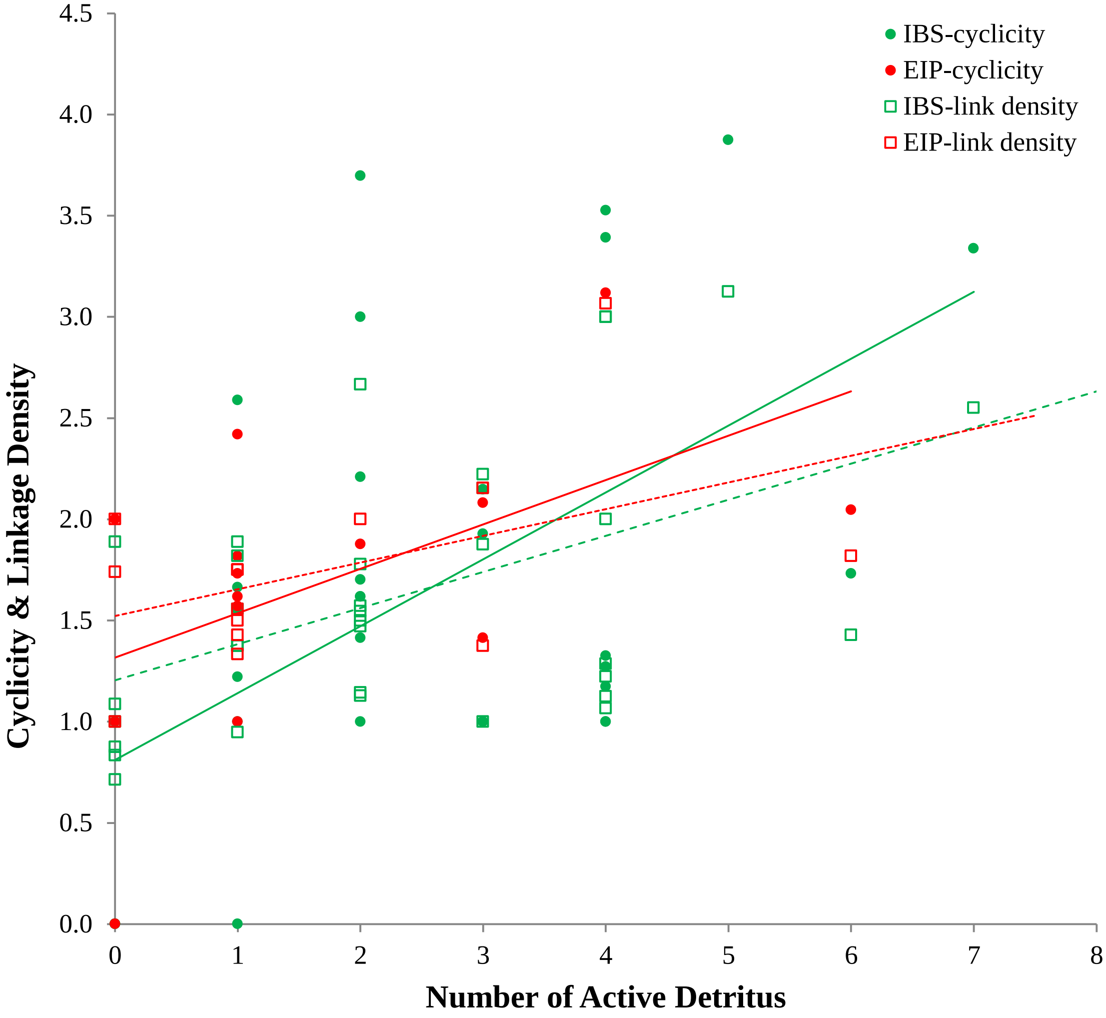


Figure 34: Linkage density (open circles and dotted lines) and cyclicity (closed circles and solid lines) comparisons between EIPs with (green - IBS) and without (red - EIP) an agricultural component, in terms of the number of active detritus actors in the system.

Increases in the number of active detritus in the system have a positive effect on both cyclicity and linkage density for both EIPs with and without agriculture. The active detritus appears to have a stronger effect on cyclicity than linkage density regardless of the presence of agriculture. This confirms that the role of the here defined detritus-type actors in an EIP is comparable to the detritus in an ecosystem - they create more internal cycling within the system and increase the number of linkages.

The impact on cyclicity of the presence of a detrital-type actor was strongest among the EIPs with an agricultural component. The weakest effect of the presence of a detrital-type actor was on linkage density when the EIP did not have an agricultural component. Figure 34 suggests that the presence of agriculture in an EIP does not increase the presence of detrital-type actors. The median number of detritus-type actors in the 34 EIPs with agriculture was 2 and for the 14 EIPs without agriculture was 1. Two thirds of the detritus-type actor functions, wastewater treatment, recycling, and recovery, are not a type of agricultural activity though, so this trend only tells us that there appears to be no one type of detritus-actor in an EIP which causes more of these types of to exist.

### 5.4.6 Food Web Functional Roles in EIPs: Decomposers and Cannibalism

Differences between EIPs and food webs reflect the fact that important functional roles may not be represented in EIPs. Functional roles Food web ecologists have long stressed the profound impact of detrital energy pathways on many facets of ecological systems (Husar 1994, Korhonen 2001, Fath and Halnes 2007).

> *"Without fungi to break things down, the earth would long ago have suffocated beneath a blanket of organic matter created by plants; the dead would pile up without end, the carbon cycle would cease to function, and living things would run out of things to eat. We tend to train our attention and science on life and growth, but of course death and decomposition are no less important to natures operations, and the fungi are the undisputed rulers of this realm"* (Pollan 2006).

Over half of all the material in a food web is connected to a decomposer-type species such as fungi, which recycles unused material and returns it back to the system. Ecological systems, particularly mature ones, are associated with a high degree of internal recycling of energy and materials, such that the amount of new inputs to the system is small compared to what is transformed among the system components (Odum 1969). Less than 10% of the annual net production in a mature forest system is consumed (by grazing) in a living state, most is used as dead matter (detritus) through delayed and complex pathways (Odum 1969). Cannibalism also is abundant in food webs (Polis 1981, Woodward and Hildrew 2002). For example salamanders, ground squirrels, dragonflies, and even chimpanzees are all known to participate in different types of cannibalistic interactions. Cannibalism has been shown to have a strong influence on the dynamics and structure of communities and entire ecosystems (Persson, Roos et al. 2003).

The EIPs here fall closest to those food webs without detrital or cannibalistic components (*FW NoDetritus* and *FW NoCannibalism* in Figure). EIPs also more closely resemble food webs collected prior to 1993 (*FW Before 1993* in Figure), which is most likely due to the infrequency of detrital components and cannibalism documentation prior to the shift in food web characterization methods. Without the functional roles of cannibalism and detritus/decomposers it is unlikely that high cyclicity values can be achieved in EIPs. This suggests that EIP designers must incorporate analogous interactions in their industrial networks to achieve the strong cycling characteristic of food webs.

Decomposers and detritivores, or species that consume detritus (dead organic matter in food webs), ensure the presence of food web pathways that include all other species in the system. The connections due to this consumption pattern contribute to all other existing cycles. Even limited connections to an actor that functions similarly in an EIP would dramatically increase connectivity, and thereby efficiencies.

Cannibalism from a purely mathematical viewpoint allows for *N* additional linkages in the system resulting in higher linkage density and connectance values than if cannibalism is absent. Analogous interactions for cannibalism in an industrial setting are possible; it is perfectly plausible that a company in an EIP could use its own byproduct, or even recycle products that have quality defects into new products. These interactions types have not been found specifically documented in the literature to date, however this may be an artifact of the lack of importance placed on these interactions in the food web literature when EIPs were first being investigated. Including them in the future will provide a much better understanding of the key components of ecosystem structure that have evolved to make them ultimately sustainable (Jelinski, Graedel et al. 1992).

### 5.4.7 Species Aggregation in Eco-Industrial Parks

Ecologists frequently aggregate species in an ecosystem into trophic species when they simplify ecosystems to food webs for analysis. The goal of aggregation is that ecosystem structure viewed from the less detailed perspective of food webs provides a happy medium: better predictions than would be made at a scale of “all species” but more functional than conclusions obtained from the scale of individual species (Wilson 1999). This aggregation can be easy to miss as ecologists tend to drop the descriptor ‘trophic’ early on, or do not use it all. The effect of this on the ecological analyses of EIPs has been that companies in an EIP have been set analogous to species in a food web without much thought. Some ecological metrics, species evenness and species richness for example, depend heavily on the way species are defined, and a misunderstood definition can cause significant changes in results, such as happened in the analysis of the Burnside Park EIP (Wright, Cote et al. 2009) as discussed in section 3.2.3.1. The designation of every company being a species in an EIP creates a structural analogy with food webs rather than a functional analogy, which would be more accurate in many ways. In the structural analogy, where every company is arbitrarily a species, the workers in a company become the individuals who interact. The value or activity of the company is only weakly correlated, if at all, with worker number. In a more functional analogy, where company function is used as an aggregating factor, the companies are the individuals who are interacting, falling more in line with the actual functioning of an EIP. This later method of aggregation does not prohibit every company from being a unique species in the system; it does however make the choice of what is a species a cognizant one. If each company is defined as a unique species, an attribute does need to be defined such that it represents the *abundance* of that species. Table 12 tests the effects of species aggregation on ten EIPs. Some EIPs were given three different species groupings and some two. An example of the resultant EIPs after species aggregation is shown in Figure 35 for the first EIP in Table 12, AES Montville. Trial #1 in all cases is the standard format where every company is a species, and represents the EIP as reported in Table D55. In some cases the reorganization of species does make a difference in the calculated metrics. Some of the metrics are expected to be strongly dependent as determined by their defining equations, such as species richness, connectance, and linkage density. The number of links in the system did not change if companies that were combined into one species were not originally linked. A dependence on the specific companies that were aggregated into one was the deciding factor for all metrics that are not directly proportional to the number of species. It can be said with confidence that for those metrics which are directly proportional to species number (connectance, number of prey, number of predators, and species richness) that species aggregation will affect the results. For the other metrics however it does not appear that we can say with any confidence that species aggregation will not affect the outcome.

Table 12: Data from the tests of species aggregation in ten eco-industrial parks. Each trial tests a different method of species aggregation, beyond the standard 'species equals company.' The trials are run on ten EIPs from the collected dataset in Table D55.

| **EIP** | Trial # | Species | Species Richness | Links | Cyclicity | Connectance | Link Density | Prey-Predator ratio | Spec-Predator fraction | Generalization | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AES Montville | *1* | *8* | *8* | *13* | *1.47* | *0.20* | *1.63* | *1.6* | *0.2* | *2.6* | *1.63* |
| | *2* | *5* | *5* | *10* | *2* | *0.4* | *2* | *1.67* | *0* | *3.33* | *2* |
| | *3* | *7* | *7* | *11* | *1.47* | *0.22* | *1.57* | *1.4* | *0.4* | *2.2* | *1.57* |
| An Son Village | *1* | *3* | *3* | *2* | *0* | *0.22* | *0.67* | *1* | *1* | *1* | *1* |
| | *2* | *2* | *2* | *2* | *1* | *0.5* | *1* | *1* | *1* | *1* | *1* |
| Connecticut Newsprint | *1* | *6* | *6* | *5* | *0* | *0.14* | *0.83* | *0.4* | *1* | *1* | *2.5* |
| | *2* | *4* | *4* | *4* | *1* | *0.25* | *1* | *0.5* | *1* | *1* | *2* |
| | *3* | *5* | *5* | *5* | *1* | *0.2* | *1* | *0.4* | *1* | *1* | *2.5* |
| Devons | *1* | *21* | *21* | *30* | *1.73* | *0.07* | *1.43* | *1.21* | *0.57* | *2.14* | *1.76* |
| | *2* | *12* | *12* | *21* | *2* | *0.15* | *1.75* | *1.38* | *0.25* | *2.63* | *1.91* |
| Fushan Farms | *1* | *7* | *7* | *9* | *1.27* | *0.18* | *1.29* | *0.71* | *0.71* | *1.29* | *1.8* |
| | *2* | *6* | *6* | *8* | *1.41* | *0.22* | *1.33* | *0.67* | *0.67* | *1.33* | *2* |
| | *3* | *3* | *3* | *4* | *1.32* | *0.44* | *1.33* | *1* | *0.67* | *1.33* | *1.33* |
| GERIPA | *1* | *8* | *8* | *14* | *1.93* | *0.22* | *1.75* | *0.75* | *0.375* | *1.75* | *2.33* |
| | *2* | *6* | *6* | *12* | *2.11* | *0.33* | *2* | *0.83* | *0.17* | *2* | *2.4* |
| Gladstone | *1* | *8* | *8* | *7* | *0* | *0.11* | *0.875* | *2* | *0.33* | *2.33* | *1.17* |
| | *2* | *6* | *6* | *6* | *1* | *0.17* | *1* | *1.67* | *0.33* | *2* | *1.2* |
| Green Triangle | *1* | *8* | *8* | *25* | *3.87* | *0.39* | *3.13* | *0.875* | *0.25* | *3.125* | *3.57* |
| | *2* | *6* | *6* | *14* | *2.83* | *0.39* | *2.33* | *0.83* | *0.33* | *2.33* | *2.8* |
| Clark Special Economic Zone | *1* | *20* | *20* | *51* | *3.34* | *0.127* | *2.55* | *0.89* | *0.26* | *2.68* | *3* |
| | *2* | *13* | *13* | *27* | *3.56* | *0.16* | *2.08* | *0.83* | *0.50* | *2.25* | *2.7* |
| | *3* | *13* | *13* | *28* | *3.02* | *0.17* | *2.15* | *0.92* | *0.42* | *2.33* | *2.55* |
| Uimaharju | *1* | *6* | *6* | *10* | *2* | *0.28* | *1.67* | *0.83* | *0.67* | *1.67* | *2* |
| | *2* | *3* | *3* | *3* | *1* | *0.33* | *1* | *1.5* | *0.5* | *1.5* | *1* |

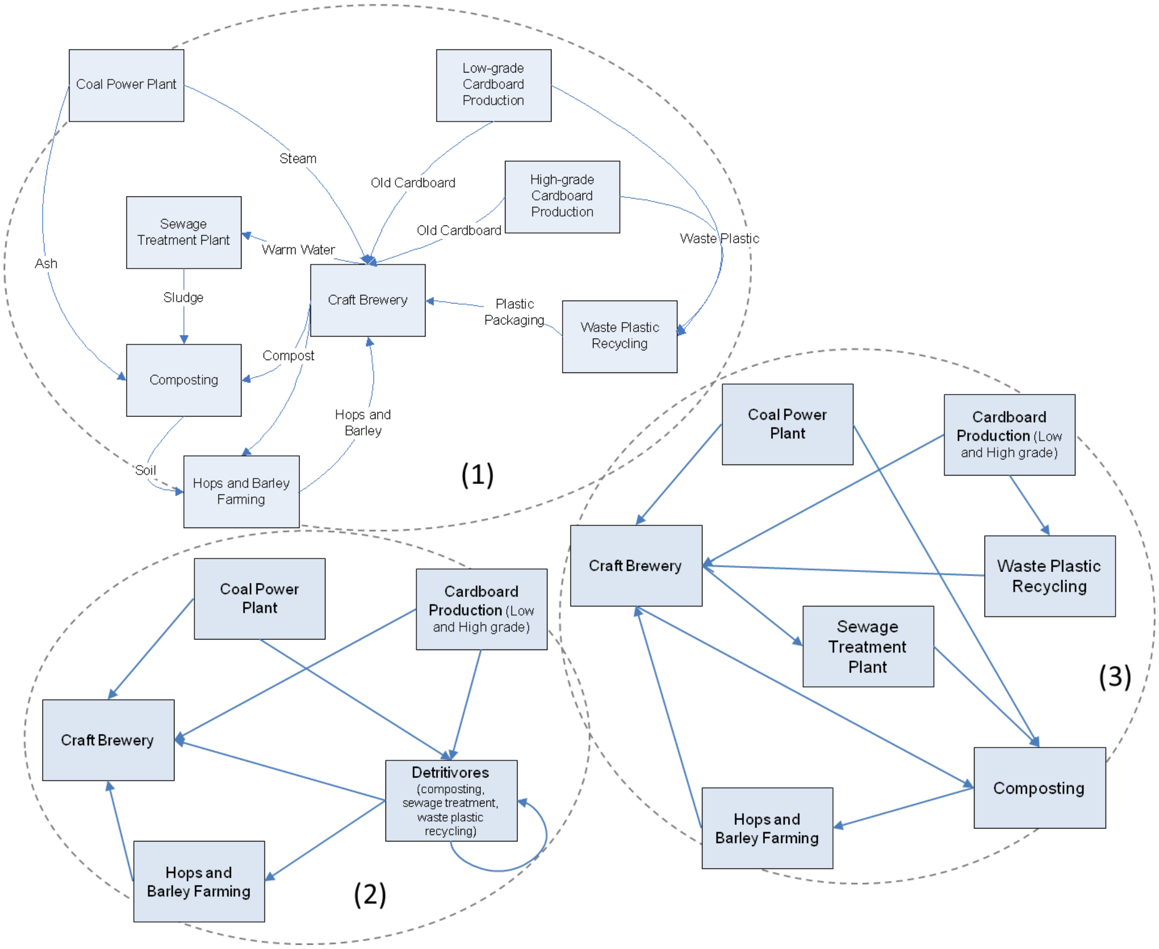


Figure 35: AES Montville species definitions. (1) Trial 1 with 8 species. (2) Trial 2 with 5 species. (3) Trial 3 with 7 species.

## 5.5 Conclusions

Progress in the study of eco-industrial parks had been limited by a lack of awareness of industry-wide policy changes to the collection and documentation of food webs. Early food web data sets are unreliable and were developed for the specific purposes of each ecological research group. When used for EIP comparisons, early data has been shown to give inaccurate conclusions regarding the biological-ness of EIPs. A collection of food webs whose median values represent a current depiction of food web structure and behavior is proposed here to be those food webs collected from 1993 and on. These food webs are much more likely to include important functional groups such as cannibalism and decomposers. Also proposed is that out of the three available organizational matrices used by ecologists, a food web matrix [**F**] should be used to calculate metrics for EIPs and any comparison food webs. This is the first time EIPs have been consciously compared to ecologically accepted food web data.

A reliable and comprehensive eco-industrial park data had not been previously available, limited progress in the design of sustainable industrial networks. An expansive EIP dataset is presented here, allowing for a large scale and comprehensive food web analysis of EIPs for the first time. The eco-industrial park dataset presented here is more than twice the size and far more detailed than those offered previously.

Using traditional and newer food web metrics and a more ecologically correct understanding of how they are calculated, the collected EIPs are shown to follow some properties of biology's naturally sustainable systems through their characteristic symbiotic relationships, but overall these networks still have a ways to go to meet the resilient and efficient properties of nature's long maturing networks. At best, these EIPs mimic those food webs lacking cannibalism and decomposers, two very important components in creating the desirable cyclical structure of food webs. The detritivores and decomposers as a group allow energy to flow unrestricted to any location in the system and process a large percentage of the total energy making them fundamentally different from any other functional group. This suggests that EIP designers must incorporate analogous interactions in their industrial networks to achieve the strong cycling characteristic of food webs. Even limited connections to an actor in an EIP that functions similarly to a decomposer in a food web would dramatically increase connectivity, and thereby efficiencies. Through an investigation of different types of actors in EIPs that fill the role of detritus/decomposer, with a focus on agriculture, there appears to be no one type of actor that causes more actors in the EIP to begin to function similarly.

Cyclicity is one measure of internal cycling in a network, in EIPs this is representative of efficient materials and energy use in the system. As energy and materials savings in EIPs are highly dependent on the successful cycling of waste and byproducts, cyclicity is an important metric. The median value for EIPs falls 55% below that of food webs, highlighting the less complex internal cycling present in the structure of EIPs as compared food webs. Cyclicity had been claimed in some literature to be dependent on system size. The large size differences found between EIPs and FWs thus required a closer look at the size dependence of cyclicity as well as the other potentially sensitive food web metrics being used. Increases in cyclicity were found not to be an artifact of increases in system size for the datasets used here.

Those metrics that are directly proportional to species or actor number (connectance, number of prey, number of predators, and species richness) were found to be affected by differences in species number between networks and for changes in species number due to species aggregation. Those metrics that are normalized by the number of actors (linkage density, generalization, vulnerability, prey to predator ratio, and specialized predator fraction) can be used to compare behavior in networks of different sizes; however it cannot be said with confidence from the analysis here whether or not other metrics investigated are affected by species aggregation in EIPs.

An exclusive actor is defined here as an actor that only acts as predator or only prey, or only consumes or produces materials and energy. Possible upper bounds for ensuring internal cycling is present in EIPs were found for the percentage of actors that are exclusively consumers or producers. They were that in an EIP fewer than 60% of actors may be exclusively predator and fewer than 40% of actors may be exclusively prey. Food webs also showed bounds for the presence of exclusive actors. Food webs seem to be characteristic of a percent of exclusive predators below 45% and a percent exclusive prey below 35%. These characteristics of the food web population are lower than what is seen for the EIPs investigated, especially for the predators. Those food webs with cyclicity greater than 4.0 had no documented exclusive predators in the system. There was only one food web in the dataset that did not contain any exclusive prey. The relatively low upper bound for the exclusive prey is interesting and may help better guide EIP designers if the bound holds for other measures of EIP success.

# CHAPTER 6

# PATTERNS IN ECO-INDUSTRIAL PARKS

## 6.1 Research Questions to be Addressed

Eco-industrial parks (EIP) have become a popular manifestation of sustainable initiatives around the world. EIP examples and proposals have met with varying success. This chapter ranks the collected EIPs based on selected food web metrics used by ecologists that classify structurally important characteristics, such as internal cycling in the network structure.  A comparison of average food web values from Appendix B to average values for the eco-industrial parks from Appendix D moves us towards a better understanding of the level of success EIPs have in mimicking their biological inspiration. This all leads into answering the following research questions:

1) What makes an EIP good or bad?
2) What prevents them from better imitating food webs?
3) How can their design further progress towards that goal?

The results of these comparisons give insight into which structural properties eco-industrial park designers may focus on to better imitate the efficient and sustainable cycling representative of biological networks. The results also help to identify fundamental physical relationships responsible for the correlation between food web network patterns and environmentally superior industrial network designs, one of the goals of this research.

## 6.2 Methods: EIP Ratings and Ranking Criteria

The goal of biologically inspired industrial networks is to mimic the sustainable cycling and recycling which is characteristic of ecosystems, ideally achieving a highly efficient closed-loop flow of materials. This chapter looks to see how well proposed vs existing EIPs correlate with natural ecosystems when using ecosystem metrics for comparison. For this purpose, several EIPs were from literature were identified and grouped.

The three main rating categories for the EIPs are based on the current (or as current as possible) status of the EIP.

G1) The EIPs in group 1 (*G1*) are all proposed systems collected from the literature. These networks are often based on an existing industrial park where the investigator has suggested additional linkages between existing and new companies to increase the symbiotic relationships.

G2) The EIPs making up group 2 (*G2*) are currently (or as current as possible) active/in operation/existing. These EIPs are often termed 'successful' in the literature as they have been fully or mostly implemented and are still running.

G3) The EIPs making up group 3 (*G3*) were fully or mostly implemented but for one reason or another, whether it was for economic or other reasons, are no longer in operation.

The four subsequent ranking categories for the EIPs are based upon the status (existence and complexity) of the internal cycling within the system. This is determined by way of the ecological metric cyclicity, calculated as the maximum real eigenvalue of the systems adjacency matrix, equation 16 in the literature review. The metric cyclicity is especially important for the design and analysis of these industrial systems, as it aids in understanding the discrepancy between natural and industrial ecosystems. The metric, which is used by ecologists to measure the presence and strength of the internal structural cycling of materials and energy in a system, embodies the major goal for eco-industrial networks: closed-loop manufacturing.

A. The EIPs with a designation of class *A* are representative of highly complex internal cycling. This is defined as those EIPs with a cyclicity value **greater than or equal to 3** ($\lambda_{max} \geq 3$). These EIPs represent the top tier of collected systems.

B. The EIPs with a designation of class *B* are representative of complex internal cycling. This is defined as those EIPs with a cyclicity value **greater than 1** ($3 > \lambda_{max} > 1$).

C. The EIPs with a designation of class *C* contain simple internal cycling. This is defined as those EIPs with a cyclicity value **equal to 1** ($\lambda_{max} = 1$).

D. The EIPs with a designation of class *D* have no internal cycling present. This is defined as those EIPs with a cyclicity value **equal to 0** ($\lambda_{max} = 0$). All of the EIPs in this grouping pass along a byproduct to another industry for use rather than disposal; however they do not have the more complex cycling that results from the reintroduction of that byproduct into the system.

Thus all EIPs in the collection have been given a designation of *G1*, *G2*, or *G3* and a ranking of *A*, *B*, *C*, or *D* class.

## 6.3 Results: EIP Ratings and Ranking

### 6.3.1 EIP Group 1-3 Comparisons

The 48 EIPs collected are organized into three groups. The groups are chosen based on the current (at the time of the data collection) knowledge as to the status of the EIP. Group 1 are those EIPs that have been proposed on paper but do not yet exists. Some of the 11 EIPs listed in Table 13 are based on existing industrial parks, but modifications suggested to transform the network into an EIP have not been realized. Some of these EIPs exist entirely on paper.

Table 13: 11 proposed EIPs from the literature.

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **Group 1 : Proposed EIPs** | *14* | *A* | The Green Triangle | 3.87 | 3.13 | 1.14 | 3.57 | 3.13 |
| | *36* | *A* | Renova (RRP) | 3.39 | 3.00 | 1.00 | 3.00 | 3.00 |
| | *6* | *A* | Clark Special Economic Zone | 3.34 | 2.55 | 0.890 | 2.68 | 3.00 |
| | *29* | *B* | Mongstad EIP | 1.55 | 1.82 | 0.800 | 1.57 | 2.50 |
| | *35* | *B* | Red Hills EcoPlex | 1.33 | 2 | 1.00 | 1.75 | 2.00 |
| | *11* | *B* | GERIPA (IBS) | 1.93 | 1.88 | 1.33 | 1.80 | 1.88 |
| | *26* | *C* | Lower Mississippi Corridor | 1 | 1.74 | 0.778 | 1.23 | 2.86 |
| | *39* | *C* | Stoneyfield Londonderry EIP | 1 | 2.15 | 0.833 | 1.57 | 2.80 |
| | *34* | *C* | PV Symbiosis Prop | 1 | 1.6 | 0.750 | 3.00 | 2.33 |
| | *13* | *D* | Gladstone (with potential links 2008) | 0 | 1.087 | 1.08 | 1.17 | 1.79 |
| | *7* | *D* | Connecticut Newsprint | 0 | 0.83 | 0.400 | 2.68 | 2.50 |

Group 2 is a collection of 31 EIPs that at the time of this writing were operational. These EIPs, listed in Table 14, count among the few that have been successfully implemented. The locations of the EIPs listed span the globe, ranging from various locations in the USA to China to Denmark and France.

Table 14: 31 Eco-Industrial Parks that have been successfully implemented (Group 2).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **Group 2 : Real EIPs** | *33* | *A* | Pomacle-Bazancourt | 3.70 | 2.67 | 1.00 | 3.00 | 3.00 |
| | *8* | *A* | Copper Industry Web | 3.12 | 3.07 | 0.92 | 3.54 | 3.83 |
| | *24* | *A* | Kytakyushu RRP | 3.00 | 1.55 | 0.80 | 1.70 | 2.13 |
| | *3* | *B* | Barceloneta | 1.41 | 1.14 | 0.571 | 0.750 | 2.00 |
| | *5* | *B* | Burnside Park EIP | 2.05 | 1.82 | 0.900 | 2.20 | 2.22 |
| | *9* | *B* | Devens EIP | 1.73 | 1.43 | 0.765 | 3.54 | 2.31 |
| | *10* | *B* | Fushan Farms IBS | 1.27 | 1.29 | 1.40 | 1.76 | 1.29 |
| | *15* | *B* | Guayama | 1.62 | 1.33 | 0.667 | 3.57 | 2.00 |
| | *16* | *B* | Guitang Sugarcane EIP Project | 1.70 | 1.78 | 0.778 | 1.33 | 2.29 |
| | *17* | *B* | Harjavalta Industrial Area | 2 | 2 | 0.833 | 1.78 | 2.40 |
| | *18* | *B* | Humber Industrial Symbiosis Project | 2.21 | 1.47 | 0.643 | 2.00 | 2.78 |
| | *20* | *B* | Kalundborg EIP | 1.62 | 1.5 | 0.538 | 1.00 | 3.00 |
| | *21* | *B* | Kawasaki | 1.88 | 2 | 1.00 | 1.62 | 2.00 |
| | *22* | *B* | Kwinana | 2.59 | 1.89 | 0.792 | 2.00 | 2.68 |
| | *30* | *B* | Nanning Sugar Company | 1.221 | 1.375 | 0.750 | 2.00 | 1.83 |
| | *37* | *B* | Scotia Investments | 1.570 | 1.43 | 1.40 | 3.00 | 1.43 |
| | *38* | *B* | Seshasayee Paper and Board Ltd.: Agro Industrial Eco-complex | 1.618 | 1.57 | 0.857 | 2.00 | 1.83 |
| | *41* | *B* | Suzhou Eco-Industrial Park | 1.732 | 1.56 | 0.889 | 1.57 | 1.75 |
| | *42* | *B* | Tianjin Economic Development Area | 1.664 | 1.38 | 1.33 | 1.56 | 1.38 |
| | *44* | *B* | Tunweni Brewery (IBS) | 1.174 | 1.125 | 0.875 | 2.25 | 1.29 |
| | *45* | *B* | Uimaharju Forest Industry Park | 2.148 | 2.22 | 0.889 | 1.13 | 2.50 |
| | *46* | *B* | Ulsan Industrial Park | 2.419 | 1.75 | 1.00 | 2.22 | 2.00 |
| | *47* | *B* | UPM Kymi pulp and paper mill | 2.081 | 2.15 | 1.20 | 2.00 | 2.33 |
| | *2* | *C* | An Son Village | 1 | 1 | 0.750 | 3.00 | 1.00 |
| | *19* | *C* | Jyvaskyla | 1 | 1 | 0.500 | 1.79 | 2.00 |

Table 14 continued: 31 Eco-Industrial Parks that have been successfully implemented (Group 2).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **Group 2 : Real EIPs** | *25* | *C* | Landskrona | 1 | 1.07 | 0.769 | 1.70 | 1.60 |
| | *28* | *C* | Monfort Boys Town (IBS) | 1 | 1.22 | 1.00 | 2.43 | 1.57 |
| | *40* | *C* | Styrian Recycling Network | 1 | 1.13 | 0.821 | 2.33 | 1.91 |
| | *27* | *D* | Lubei Industrial Park | 0 | 1.89 | 1.14 | 2.22 | 2.13 |
| | *12* | *D* | Gladstone 2005 | 0 | 0.875 | 0.500 | 2.50 | 2.33 |
| | *33* | *D* | Pingdingshan Coal Mining Group | 0 | 1.00 | 1.00 | 1.11 | 1.33 |

The three EIPs in group 3 have all been documented as having failed. These EIPs, listed in Table 15, were put into operation and for any number of reasons they no longer exist. News reports on AES Thames explain that money issues were at the heart of its failure. It is highly likely that the other two EIPs had similar issues.

Table 15: Three failed EIPs from the literature.

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **Group 3 : Failed EIPs** | *1* | *A* | AES Thames EIP | 3.53 | 3.00 | 1.00 | 3.00 | 3.00 |
| | *4* | *B* | Brownsville EIP | 1.41 | 1.38 | 1.20 | 1.14 | 1.83 |
| | *43* | *D* | Triangle J EIP | 0 | 0.95 | 1.88 | 1.83 | 1.20 |

### 6.3.2 EIP Class *A*-*D* Comparisons

The 48 EIPs listed Appendix D are ranked in terms of their success in reaching a biologically inspired state using cyclicity ($\lambda_{max}$), linkage density ($L_D$), the prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$). The other five metrics used in this paper were not selected as they are all affected by network size (species number, links, prey, predator, and connectance).

### 6.3.2.1 A Class EIPs

Seven EIPs make up the top performers in class A highlighted in Table 16. All of the EIPs in this group have cyclicity greater than three (3), exhibiting the most complex internal cycling in the group.

Table 16: The top seven performers in the EIP dataset with a ranking of *A* class, compared to median values for the 50 food webs collected after 1993. The five metrics used in ranking the success of the EIPs are cyclicity ($\lambda_{max}$), linkage density ($L_D$), prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **Top Seven EIPs (A class)** | *14* | *Proposed* | The Green Triangle | 3.87 | 3.13 | 1.14 | 3.57 | 3.13 |
| | *33* | *Exists* | Pomacle-Bazancourt | 3.70 | 2.67 | 1.00 | 3.00 | 3.00 |
| | *1* | *Failed* | AES Thames EIP | 3.53 | 3.00 | 1.00 | 3.00 | 3.00 |
| | *36* | *Proposed* | Renova (RRP) | 3.39 | 3.00 | 1.00 | 3.00 | 3.00 |
| | *6* | *Proposed* | Clark Special Economic Zone | 3.34 | 2.55 | 0.890 | 2.68 | 3.00 |
| | *8* | *Exists* | Copper Industry Web | 3.12 | 3.07 | 0.92 | 3.54 | 3.83 |
| | *24* | *Exists* | Kytakyushu RRP | 3.00 | 1.55 | 0.80 | 1.70 | 2.13 |

The top seven EIPs listed in Table 16 have one or more detritus-type actors, this type of actor makes up half to a third of the total actors in the group. We define a detritus-type actor for an EIP as an actor that is of the type waste treatment (i.e. composting), recovery and recycling (i.e. repair, remanufacture, reuse, resale), or agriculture (i.e. farm, zoo, landscaping, green house, golf course). Additionally, to qualify as a detritus-type actor there must be at least one link entering and leaving said actor. This last criterion is based on the fundamental job description of a detritus/decomposer in a food web and ensures that the detritus-type actor is an active participant of the EIP. Four out of the seven top EIPs have some form of composting or agriculture -type actor. The EIPs in this top group tended to have a larger than average linkage density as well.

Even when fewer connections exist, and therefore the linkage density is lower, having active recyclers in the system results in complex cycling. The lowest EIP in the top group, Kytakyushu Resource Recovery Park in Japan, has a low linkage density and prey-predator ratio in comparison to the rest of the group, while still having a high cyclicity. Looking into the food web matrix for Kytakyushu (found in table 5 of the online supplementary material), we find that all of the interactions in the system are to and from only one of the eleven actors: the resource recovery facility, which is the acting detritus. Clark Special Economic Zone also has a lower linkage density as compared to a majority of the top EIPs. Of the 51 links between the 20 actors in Clark, those actors that saw the most connections were the 5 composting/processing/recovery facilities; 84% of the total links in the system passed through these detrital-type actors. The Kytakyushu RRP has 100% of the total links in the system passing through its detritus-actor.

#### 6.3.2.2 *B* Class EIPs

The class B performers in the EIP dataset are listed in Table 17 below. These EIPs are listed alongside median values for the dataset of food webs collected after 1993 for comparison. The class B performers are those EIPs that had a cyclicity value between 1 and 3, and at 25 make up the largest percentage of the EIPs collected in Appendix D. Of the 25 EIPs that make up this dataset, and all but four of the 25 were operational at the time of data collection, only one in the set was found to have failed.

Table 17: The 25 - B class performers in the EIP dataset compared to median values for the 50 food webs collected after 1993. The five metrics used in ranking the success of the EIPs are cyclicity ($\lambda_{max}$), linkage density ($L_D$), prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **B class EIPs** | *22* | *Exists* | Kwinana | 2.59 | 1.89 | 0.792 | 2.13 | 2.68 |
| | *46* | *Exists* | Ulsan Industrial Park | 2.42 | 1.75 | 1.00 | 2.00 | 2.00 |
| | *18* | *Exists* | Humber Industrial Symbiosis Project | 2.21 | 1.47 | 0.643 | 1.79 | 2.78 |
| | *45* | *Exists* | Uimaharju Forest Industry Park | 2.15 | 2.22 | 0.889 | 2.22 | 2.50 |
| | *47* | *Exists* | UPM Kymi pulp and paper mill | 2.08 | 2.15 | 1.20 | 2.80 | 2.33 |
| | *5* | *Exists* | Burnside EIP | 2.05 | 1.82 | 0.900 | 2.00 | 2.22 |
| | *17* | *Exists* | Harjavalta Industrial Area | 2.00 | 2.00 | 0.833 | 2.00 | 2.40 |
| | *11* | *Proposed* | GERIPA (IBS) | 1.93 | 1.875 | 1.33 | 2.50 | 1.88 |
| | *21* | *Exists* | Kawasaki | 1.88 | 2.00 | 1.00 | 2.00 | 2.00 |
| | *23* | *Exists* | Kymi EIP | 1.82 | 1.75 | 1.00 | 2.00 | 2.00 |
| | *41* | *Exists* | Suzhou Eco-Industrial Park | 1.73 | 1.56 | 0.889 | 1.56 | 1.75 |
| | *9* | *Exists* | Devens EIP | 1.73 | 1.43 | 0.765 | 1.76 | 2.31 |
| | *16* | *Exists* | Guitang Sugarcane EIP Project | 1.70 | 1.78 | 0.778 | 1.78 | 2.29 |
| | *42* | *Exists* | Tianjin Economic Development Area | 1.66 | 1.38 | 1.33 | 1.83 | 1.38 |
| | *38* | *Exists* | Seshasayee Paper and Board Ltd.: Agro Industrial Eco-complex | 1.62 | 1.57 | 0.857 | 1.57 | 1.83 |
| | *20* | *Exists* | Kalundborg EIP | 1.62 | 1.5 | 0.538 | 1.62 | 3.00 |
| | *15* | *Exists* | Guayama | 1.62 | 1.33 | 0.667 | 1.33 | 2.00 |
| | *37* | *Exists* | Scotia Investments | 1.57 | 1.43 | 1.40 | 2.00 | 1.43 |
| | *29* | *Proposed* | Mongstad EIP | 1.55 | 1.82 | 0.800 | 2.00 | 2.50 |
| | *4* | *Failed* | Brownsville EIP | 1.41 | 1.38 | 1.20 | 2.20 | 1.83 |
| | *3* | *Exists* | Barceloneta | 1.41 | 1.14 | 0.571 | 1.14 | 2.00 |

Table 17 continued: The 25 - B class performers in the EIP dataset compared to median values for the 50 food webs collected after 1993. The five metrics used in ranking the success of the EIPs are cyclicity ($\lambda_{max}$), linkage density ($L_D$), prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| ***B* class EIPs** | *35* | *Proposed* | Red Hills EcoPlex | 1.33 | 2.00 | 1.00 | 2.00 | 2.00 |
| | *10* | *Exists* | Fushan Farms (IBS) | 1.27 | 1.29 | 1.40 | 1.80 | 1.29 |
| | *30* | *Exists* | Nanning Sugar Company | 1.22 | 1.38 | 0.750 | 1.38 | 1.83 |
| | *44* | *Exists* | Tunweni Brewery (IBS) | 1.17 | 1.13 | 0.875 | 1.13 | 1.29 |

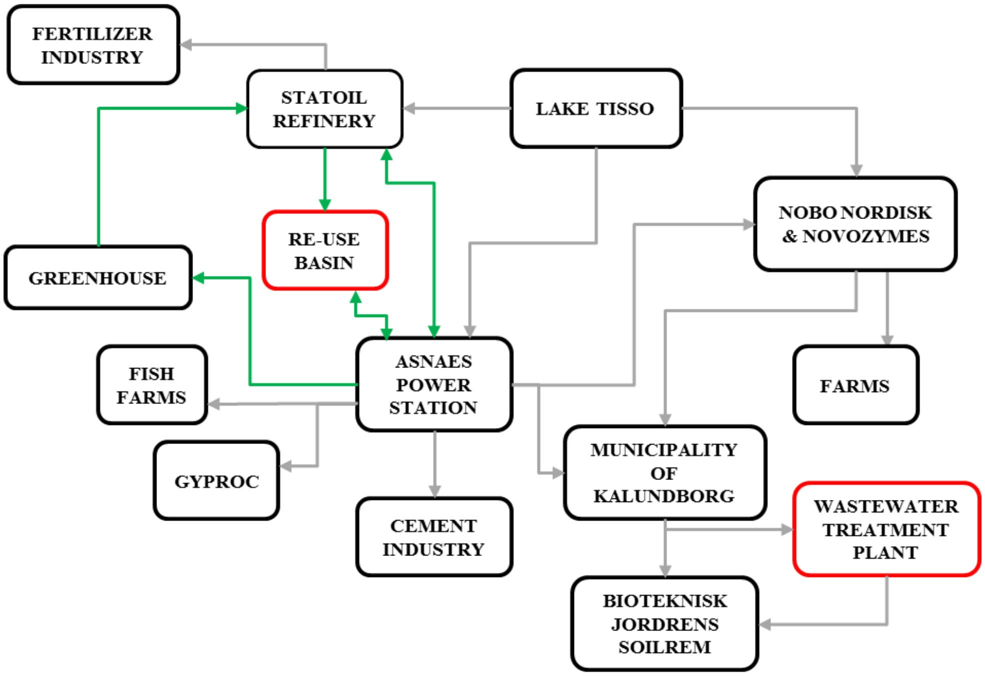
#### 6.3.2.3 *C* Class EIPs

The class C performers in the EIP dataset are listed in Table 18 below. These EIPs are listed alongside median values for the dataset of food webs collected after 1993 for comparison. The class C performers are those EIPs that had a cyclicity value of 1. Of the 10 EIPs that make up this dataset three were found to be in the proposal stage and seven operational at the time of data collection.

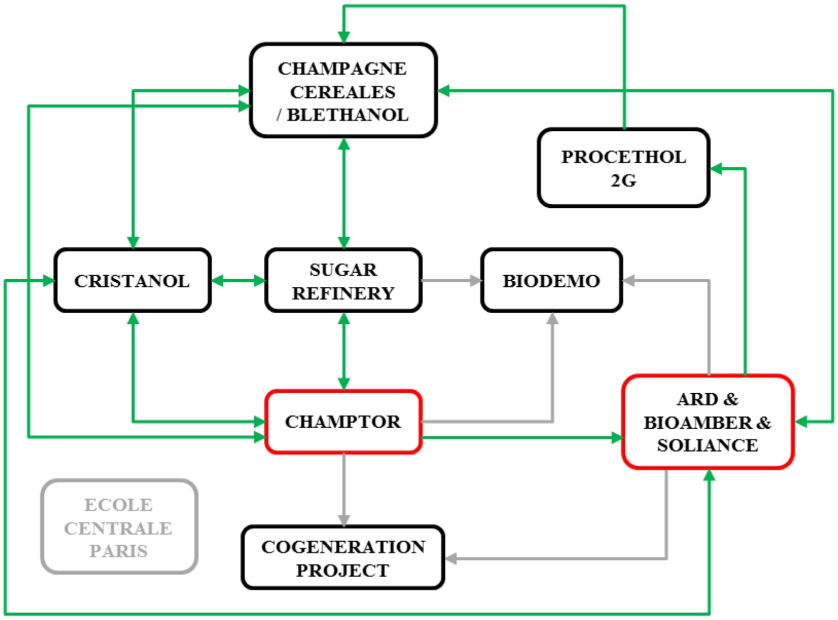
Table 18: The 10 - C class performers in the EIP dataset compared to median values for the 50 food webs collected after 1993. The five metrics used in ranking the success of the EIPs are cyclicity ($\lambda_{max}$), linkage density ($L_D$), prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **C class EIPs** | *39* | *Proposed* | Stoneyfield Londonderry EIP | 1 | 2.15 | 0.833 | 2.33 | 2.80 |
| | *26* | *Proposed* | Lower Mississippi Corridor | 1 | 1.74 | 0.778 | 2.22 | 2.86 |
| | *34* | *Proposed* | PV Symbiosis Prop | 1 | 1.56 | 0.750 | 1.75 | 2.33 |
| | *48* | *Exists* | Wallingford Eco-Industrial Park | 1 | 1.50 | 0.818 | 1.64 | 2.00 |
| | *28* | *Exists* | Monfort Boys Town (IBS) | 1 | 1.22 | 1.00 | 1.57 | 1.57 |
| | *40* | *Exists* | Styrian Recycling Network | 1 | 1.13 | 0.821 | 1.57 | 1.91 |
| | *25* | *Exists* | Landskrona | 1 | 1.07 | 0.769 | 1.23 | 1.60 |
| | *2* | *Exists* | An Son Village | 1 | 1.00 | 0.750 | 0.75 | 1.00 |
| | *19* | *Exists* | Jyvaskyla | 1 | 1.00 | 0.500 | 1.00 | 2.00 |
| | *31* | *Exists* | NIA-KIADB | 1 | 0.714 | 0.667 | 1.11 | 1.67 |

Kalundborg ranks in the bottom half of the *C* class EIPs, those exhibiting only basic internal cycling. Comparing Kalundborg to Pomacle-Bazancourt, the top ranking EIP which exists, Figure 36 highlights the level of participation of the detritus actors, outlined in red, in each system. All except one of the 15+ cycles in Pomacle-Bazancourt involve the two detritus actors. Kalundborg also has two detritus actors. The difference is that only one of the two detritus actors participates in only two of the three existing cycles. So Kalundborg has far fewer cycles and detritus actors which are disengaged from a majority of the system, while those EIPs in the top performing group have a majority of their total links involved in a cycle and highly involved detritus actors.



*Kalundborg EIP*



*Pomacle – Bazancourt EIP*

Figure 36: A comparison of the internal cycling of materials and energy within the Kalundborg and Pomacle-Bazancourt EIPs. Green arrows represent linkages which participate in a cycle, greyed out linkages do not. Actors highlighted in red are the acting detritus of the EIP.

### 6.3.2.4 *D* Class EIPs

Table 19: The 6 - D class performers in the EIP dataset compared to median values for the 50 food webs collected after 1993. The five metrics used in ranking the success of the EIPs are cyclicity ($\lambda_{max}$), linkage density ($L_D$), prey-predator ratio ($P_R$), generalization ($G$), and vulnerability ($V$).

| | | | | $\lambda_{max}$ | $L_D$ | $P_R$ | $G$ | $V$ |
|---|---|---|---|---|---|---|---|---|
| **FWs post-1993 median values (50)** | | | | 4.24 | 5.04 | 1.09 | 6.18 | 5.34 |
| **D class EIPs** | *27* | *Exists* | Lubei Industrial Park | 0 | 1.89 | 1.14 | 2.43 | 2.13 |
| | *13* | *Proposed* | Gladstone (with potential links 2008) | 0 | 1.09 | 1.08 | 1.92 | 1.79 |
| | *32* | *Exists* | Pingdingshan Coal Mining Group | 0 | 1.00 | 1.00 | 1.33 | 1.33 |
| | *43* | *Failed* | Triangle J EIP | 0 | 0.947 | 1.88 | 2.25 | 1.20 |
| | *12* | *Exists* | Gladstone (2005) | 0 | 0.875 | 0.500 | 1.17 | 2.33 |
| | *7* | *Proposed* | Connecticut Newsprint | 0 | 0.833 | 0.400 | 1.00 | 2.50 |

There are six EIPs listed in Table 19 which ranked as *D* class, exhibiting zero internal cycling. These EIPs are characteristic of a cyclicity value of zero, and lower linkage density. Connecticut Newsprint ranks the lowest out of all the EIPs in comparison to food webs. Interesting is it does in fact have a composting and a recycling component, but these actors fail to provide any benefits with regards to structure; they each only have one connection with the rest of the system. Triangle J located in North Carolina, another EIP in this bottom group, has a wastewater treatment plant which interacts with three other actors; however similar to Connecticut Newsprint, it too fails to be an “active-enough” participant to have an impact on the internal cycling. So we see it is not enough to simply have a ‘detrital’ component in an EIP, it must be an active participant in the system in order to create cycles of materials and energy. An EIP with no internal cycling seems contrary to what one expects of a bio-inspired industrial network as one of the most influential and identifying characteristics of biological networks is the prevalence and importance of materials and energy cycling within the system. Should non-zero cyclicity be a requirement for the designation of an industrial network as an EIP? This is something that may potentially be considered in the future for EIP designation similar to a LEED certification system.

### 6.3.3 Percentage Difference Between EIPs and Food Web Averages

Figure 40 visualizes the separation between biological ecosystems, in terms of the aforementioned structural metrics, and EIPs. The percent difference between average values for all EIP groupings and food web averages clearly shows that EIPs do not yet successfully mimic food webs. All ecological metric values for EIPs markedly differ with the average values calculated for ecosystems, as seen by the percent differences outlines in Figure 40; in most cases EIP values are lower. The EIP dataset is grouped into 9 levels of success in terms of both the level of biological imitation and economic status of the EIP. G1, G2, and G3 represent the status of EIPs: proposed, existing, or failed respectively and A, B, C, and D represent the level of internal cycling in the EIP: high ($\lambda_{max} \geq 3$), medium ($3 > \lambda_{max} > 1$), basic ($\lambda_{max} = 1$), and none ($\lambda_{max} = 0$) respectively. The largest and most consistent differences between EIPs and biological ecosystems occur for cyclicity and linkage density. For all metrics, those EIPs which had high cyclicity values (three or greater), whether existing or proposed, showed the smallest percent difference from food web averages. Those EIPs that had no internal cycling (cyclicity of zero) and basic internal cycling (cyclicity of one) showed the biggest percent difference from food web averages. The level of internal cycling had a much greater effect on the percent difference from food web averages than did the economic status of the EIP, whether the EIP was only proposed, in operation, or had failed those with higher cyclicity came closest to reaching food web averages.  The proposed EIPs in Figure 37 show a tendency to come slightly closer to food web averages than the existing or failed EIPs. This is most likely due to the fact that the proposed EIPs have not had to deal with the realities of operation yet; on paper one may make a very beautiful design, however in actual operation the design may not be possible.

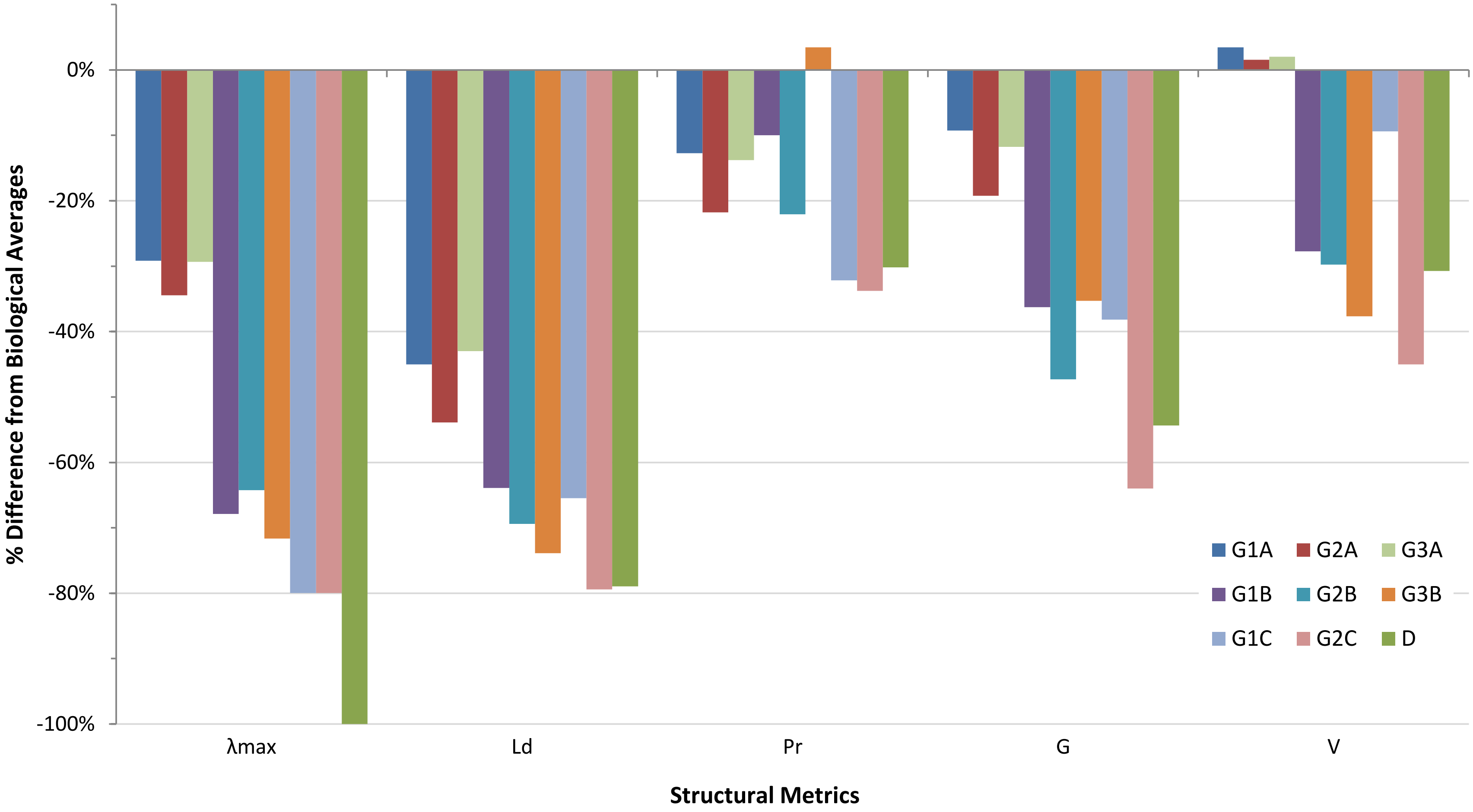


Figure 37: Percentage difference from biological averages for four structural metrics (linkage density, prey-predator ratio, generalization, vulnerability, and cyclicity) commonly used by ecologists to characterize food webs, as applied to the average values for the EIP groupings. *G1*, *G2*, and *G3* represent the status of EIPs: proposed, existing, or failed respectively. *A*, *B*, *C*, and *D* represent the level of internal cycling in the EIP: high ($\lambda_{max} \geq 3$), medium ($3 > \lambda_{max} > 1$), basic ($\lambda_{max} = 1$), and none ($\lambda_{max} = 0$) respectively.

## 6.4 Discussion

None of the EIPs identified here reach a cyclicity or density of links close to that which is found for biological ecosystems. As seen in Table 20 the closest EIP has a cyclicity of 3.87 and a linkage density of 3.13 as compared to the respective median food web values of 4.24 and 5.04. The other structural metrics calculated (ratio of prey to predators, generalization, and vulnerability) also fall short of FW median values but to a lesser degree.

Table 20: A close up of the range of food webs and EIPs in the datasets used.

| Name | $\lambda_{max}$ | $L_D$ | $P_R$ | $P_S$ | G | V |
|---|---|---|---|---|---|---|
| Post 1993 FWs *Median* | *4.24* | *5.04* | *1.09* | *0.115* | *6.18* | *5.34* |
| "*Worst*" FW | *0* | *1.59* | *1.00* | - | *1.28* | *1.28* |
| "*Smallest*" FW | *2.68* | *2.67* | *1.2* | *0.200* | *3.2* | *2.67* |
| "*Largest*" FW | *10.3* | *9.74* | *1.01* | - | *19.9* | *19.6* |
| "*Best*" EIP - The Green Triangle (*class A*) | *3.87* | *3.13* | *1.14* | *0.143* | *3.57* | *3.13* |
| "*Worst*" EIP - Connecticut Newsprint (*class D*) | *0* | *0.833* | *0.4* | *1* | *1* | *2.5* |

Figure 37 shows the metrics that have been normalized by system size (link density, prey-predator ratio, generalization, and vulnerability) as well as cyclicity. The numerical values for this figure are shown in Table 20. These metrics for EIPs when compared to median values for food webs highlight that current EIPs do not match those values characteristic of ecosystems. The values of cyclicity and linkage density, which are both metrics that characterize the type and presence of connections within the system, have a significantly larger percent difference from food web averages than the other three metrics at 62% and 64% lower than food webs, respectively. EIPs in all groupings come closest on average to matching the median values for the food web metric vulnerability (*V* – the furthest right metric in Figure 37) and prey to predator ratio ($P_R$ – center metric in Figure 37); with both metrics coming in with an average value for all EIP types 19% lower than food webs.

Vulnerability, as outlined in section 3.3.2, is the average number of connections in the system per prey-type actor and represents the number of predator species against which a species can defend (Schoener 1989). Using industrial language this represents the number of consumers a producer can support. This hints that EIPs as currently designed are close to reaching a bio-inspired balance for the number of companies which provide materials and energy to the system. This is interesting in that it relates back to Figure 29-bottom showing the percentage of total actors in the EIPs which act exclusively as prey (the actors provide materials and energy but do not receive any within the network boundaries). The apparent upper limit shown by Figure 29-bottom is that for an EIP to have at least a basic level of internal cycling in the system the percentage of total actors which are exclusively prey cannot exceed 40%.

Generalization, also outlined in section 3.3.2, is the average number of connections in the system per predator-type actor and represents the number of prey species against which a species can consume (Schoener 1989). The limit for percentage of actors which act exclusively as predators is slightly higher at around 60% as seen in Figure 29-top. The EIPs which come closest to average FW values for all metrics however are still those with the highest cyclicity ($\lambda_{max} \geq 3$). This again supports the notion that EIP designers and decision makers should be aiming for the highest cyclicity possible in their structural designs.

The results of the existing and failed EIPs are partially due to a response to external stimuli. Industrial networks from which EIPs are built are “complex adaptive systems” where the system does not adapt with any coordination but rather it is the components that change in their own best interest in response to external conditions (Kambhu, Weidman et al. 2007). EIPs experience a certain amount of purposeful coordination between the participating companies, but still experience to different degrees the complex adaptive system response. The best scenarios would be expected to be those created on paper as these have been ideally designed with the total purpose of optimizing a coordinated network behavior. These ‘proposed’ EIPs however still possess cycling well below that found in biological systems. The EIP dataset in Appendix D is made up of approximately 20% (at the time of data collection) proposed EIP that have not yet been implemented (11 of the 48 EIPs collected). It should be noted when conclusions are drawn from these EIPs that they remain proposals, they are hypothetically possible but not realized.

### 6.4.1 Cycling and Indirect Effects

What is observed in the EIP results is believed to be the difference between a simple ‘waste = food’ analogy and a truly biologically inspired food web, the two concepts are illustrated by Figure 38 (originally Figure 15, reprinted here for the readers benefit). The industrial networks of class D, all of which have a cyclicity of zero, follow the linear structure of the food chain in Figure 38-Left. Even though many of these networks exchange and re-use byproducts, the system is still made up of a linear chain of relationships, characterized by the food chain in Figure 38-Left. The industrial networks which have cyclicity greater than zero, those in classes A, B, and C, begin to show some of the ecological benefits characteristic of strong internal cycling, characterized by the food web in Figure 38-Right. The EIPs in these higher classes exhibit median values for all the metrics used here closer to medians for the food webs.

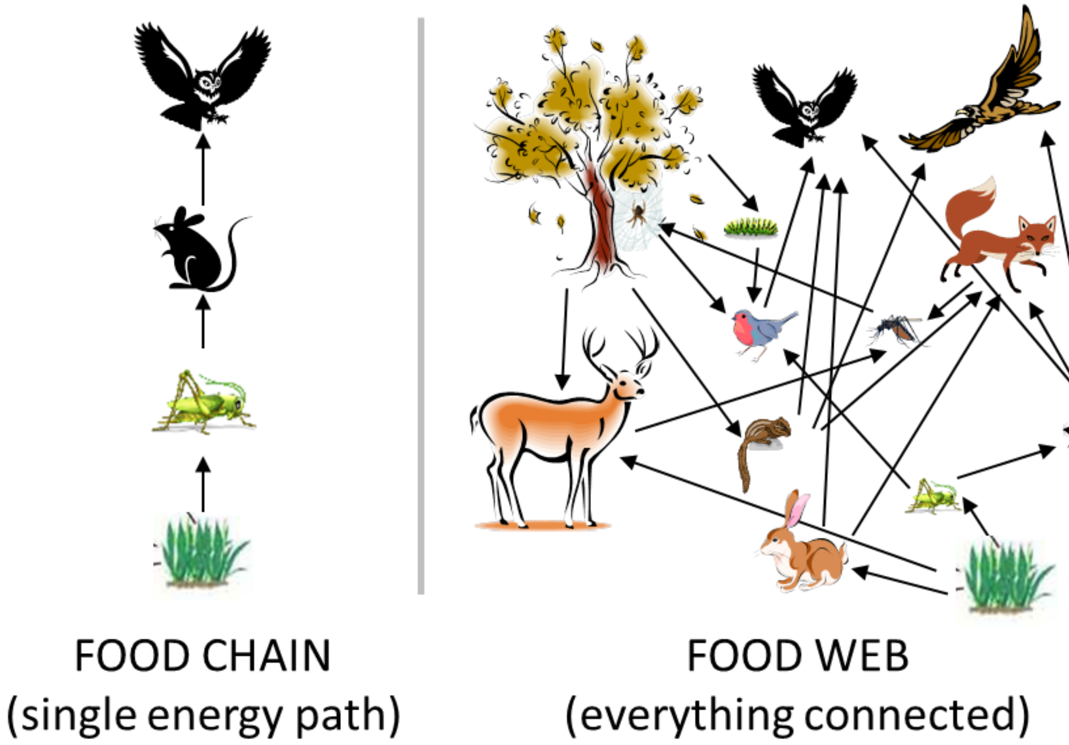


Figure 38: A dramatization of the difference in complex cyclical interactions between a food chain and a food web in nature. Adapted from (deCharon 2013).

This goal of mimicking median values of the food web metrics stems from the belief that form follows function. EIPs that match the form of FWs will function more like the food webs. The characteristic cycling seen in food webs is an especially desirable function for developing sustainable industry. This cycling of materials and energy in food webs brings with is a host of other industry desirable properties and functions. The successful establishment of cycling in EIPs can also be understood through the presence and relative strength of indirect effects.

The ecologists Salas and Borrett found that in a set of 50 food webs, when significant cycling was present indirect flows were nearly always found to dominate direct flows (Salas and Borrett 2011). As discussed in section 2.4.3 of the literature review, the last 20 years ecologists have established the dominance of indirect effects in ecosystems e.g. (Higashi and

Patten 1989). The relationship between cycling in the system and indirect effects makes it a design property of interest for industry.

The possibilities for measuring indirect effects using only structural information are limited to the measurement of paths of length greater than one. For example, a path of length two indicates an indirect effect between the two actors at either end of the path, they do not directly interact, but they do have a relationship that exists through the middle man. The rate of increase in the number of paths with path length is called the pathway proliferation rate and is measured by cyclicity. The relative magnitude of cyclicity can be used as a descriptor of indirect flows in the network. Pathway proliferation has a strong influence on the development and significance of indirect flows (Borrett, Fath et al. 2007). A faster rate of pathway proliferation, or a higher cyclicity, signifies that short indirect pathways are more numerous. Because shorter indirect pathways tend to process larger indirect flows, a higher cyclicity increases the possibility that indirect flows will dominate direct flows (Borrett, Fath et al. 2007).

Paths of specific lengths can be found by raising the adjacency matrix to a power that represent the path length being investigated (Roberts 1976, Patten 1985). Thus to find paths of length two or greater we raise the matrix [**A**] to the powers 2, 3, 4 and so on. Figure 39 shows path lengths of 1-100 for the 48 EIPs investigated. These were calculated by raising each of the adjacency matrices of the 48 EIPs to the powers 1-100. Each line in Figure 39 represents an EIP. The pathway proliferation rate for food webs has been shown to increase with a power law degree distribution (Patten, Richardson et al. 1982, Patten 1985) (Borrett, Fath et al. 2007, Fath and Halnes 2007). This relationship can be seen in Figure 39 insert (a) (Patten 1985). The curves for those EIPs with the highest cyclicity, those curves on top in Figure 39, most strongly resemble the curve found by Patten for ecosystem behavior shown Figure 39 insert (a) (Patten 1985).

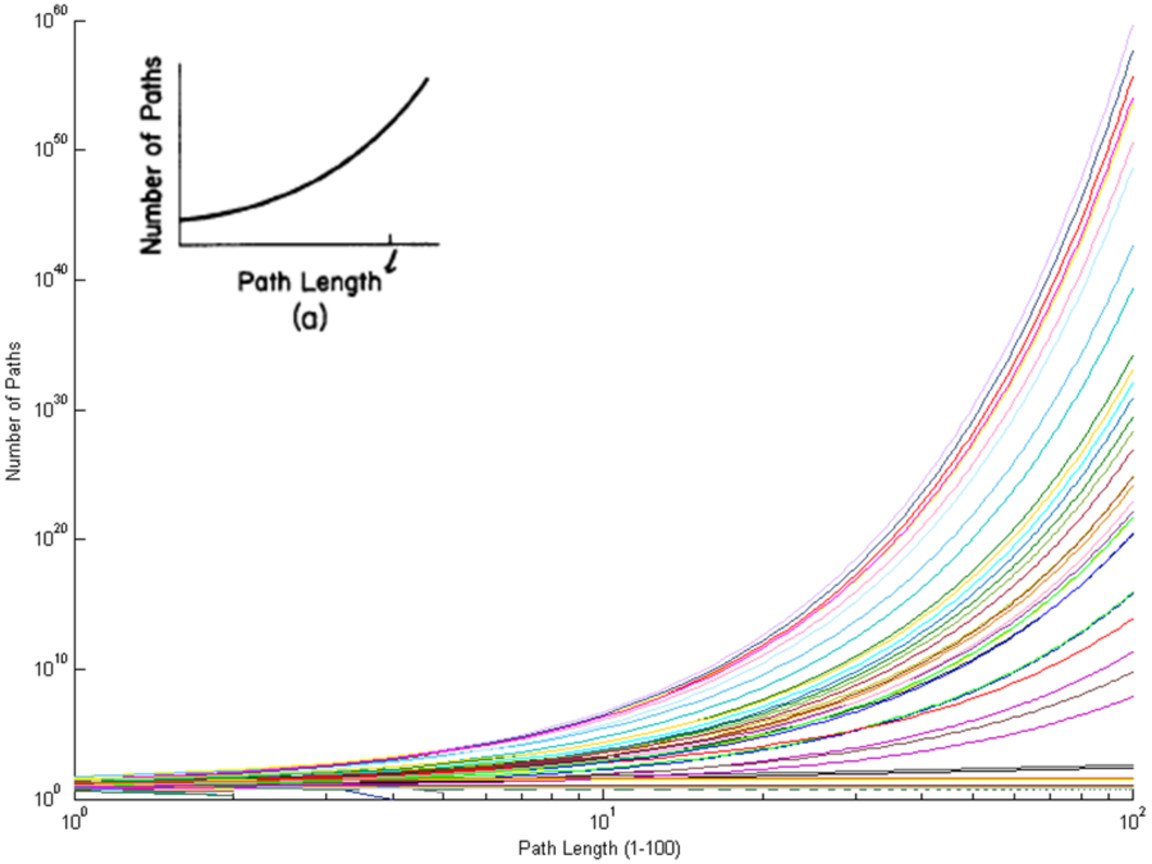


Figure 39: Path length vs number of paths totaled for the whole network in all 48 EIPs for paths of length 1 to 100, log-log scale. Insert (a) is the path length to number of paths relationship for food webs as presented by (Patten 1985).

Figure 40 through Figure 42 break down the pathway proliferation rate of the 48 EIPs plotted in Figure 39 in terms of cyclicity. The goal of this break down is to show that the relationship between indirect path lengths and the presence and strength of cycles as seen for food webs is possible in industry. This specific food web behavior is one where a few nodes in the system have a large number of connections, while most nodes in the system have very few connections (Barabási 2002).

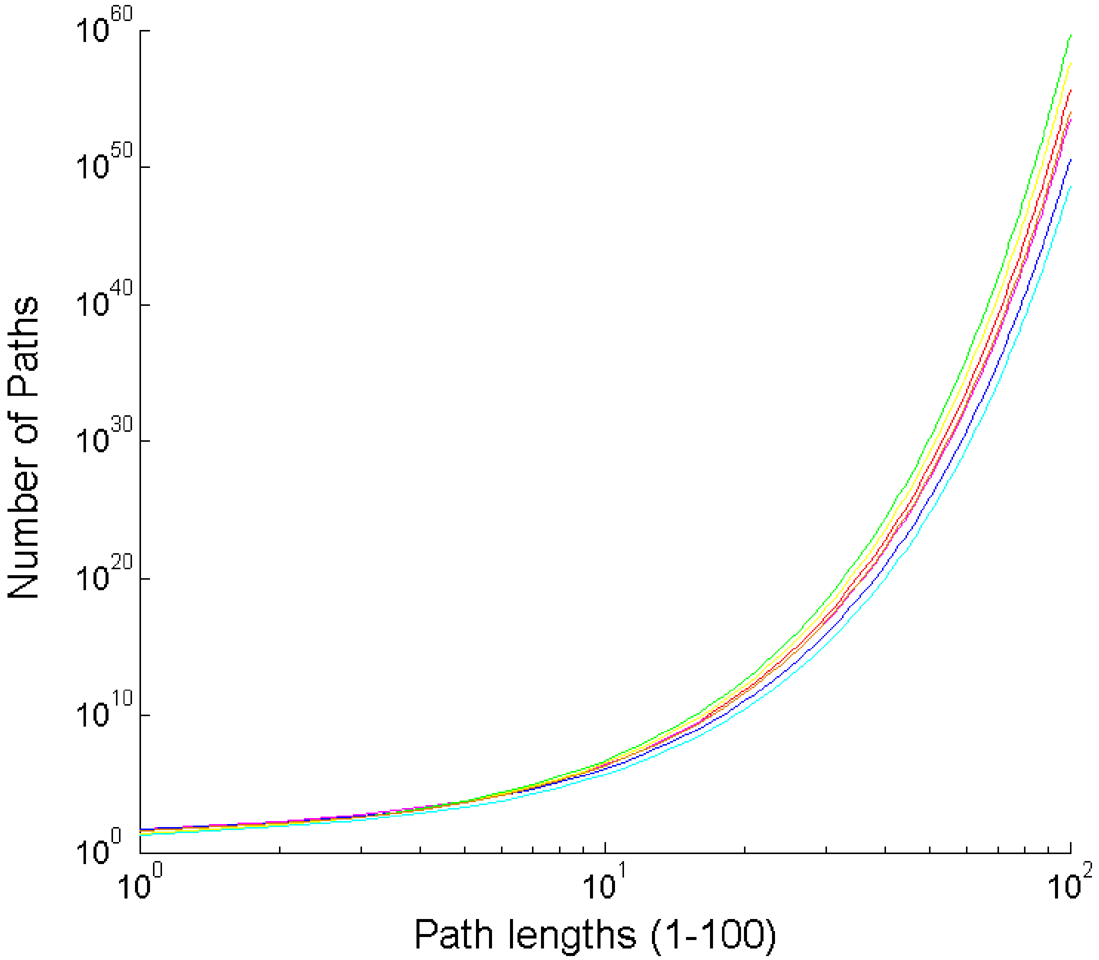


Figure 40: Path length vs number of paths for the top 7 high cyclicity EIPs, or class A (from Table 16), for paths of length 1 to 100, log-log scale.

Figure 40 plots the top seven EIPs, those in group A, that have a cyclicity of three or greater. The figure clearly shows that for the EIPs with a relatively high cyclicity (here 3 or greater) the rate of increase in the number of paths with path length is high. The power-law degree distribution seen for these EIPs in group A closely match food web behavior. This topological similarity means that the network robustness to random node deletion that has been related to this structure (Albert, Jeong et al. 2000, Dunne, Williams et al. 2002) may be translated for those EIPs which closest match the cyclicity seen in food webs. The metric robustness is unfortunately a metric that requires knowledge of the quantities of materials and energy flowing between actors, information that is not currently available for EIPs.

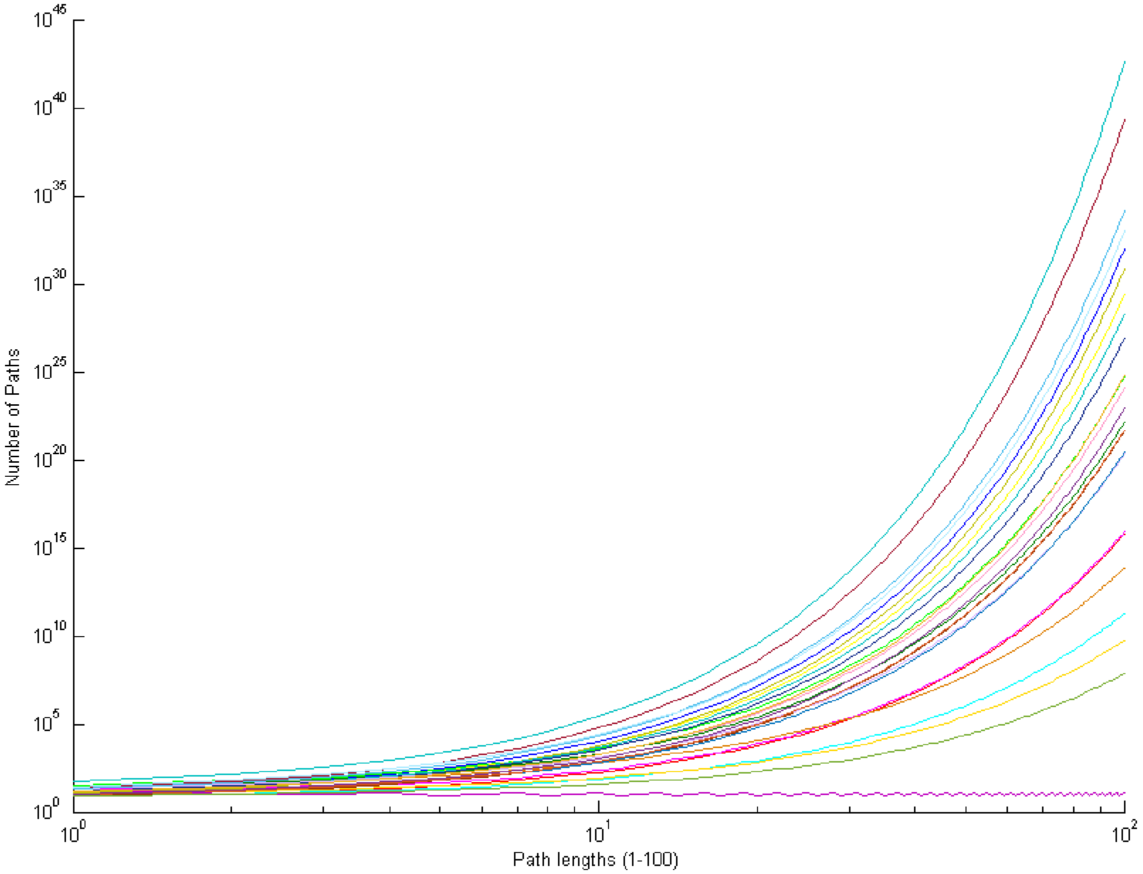


Figure 41: Path length vs number of paths for the 25 medium-high cyclicity EIPs, or class B (from Table 17), for paths of length 1 to 100, log-log scale.

Figure 41 shows the class B EIPs, those with a cyclicity greater than one. Higher cyclicity values, which translate to a faster rate of pathway proliferation, signify that short indirect pathways are more numerous. Short indirect pathways in ecosystems tend to process larger indirect flows, thus a higher cyclicity increases the possibility that indirect flows will dominate direct flows (Borrett, Fath et al. 2007). This is another supporting factor for EIP designers to strive for higher cyclicity values in their networks; EIPs with higher cyclicity will have a structure that supports a level of dominance of indirect flows that is on par with what is seen in food webs.

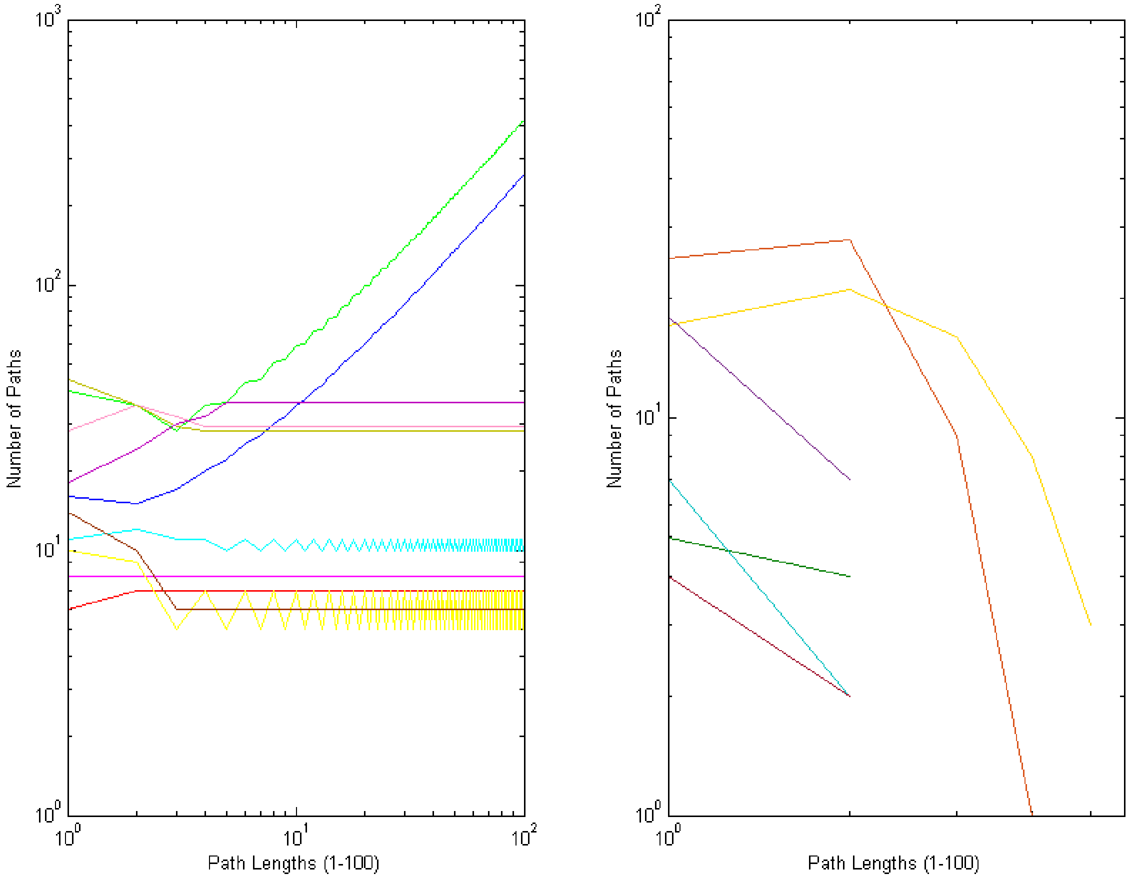


Figure 42: Path length vs number of paths for (left) the 10 medium cyclicity EIPs, or class C (from Table 18), and (right) the 10 low cyclicity EIPs, or class D (from Table 19) for paths of length 1 to 100, log-log scale.

Figure 42 shows the class C and class D EIPs. These EIPs have a cyclicity of one and zero. Figure 42-Left shows that for those EIPs with some form of basic cycling present in their structure there is no guarantee that the number of paths in the system will be able to increase with path lengths. Figure 42-Right shows that with no cycling there is no pathway proliferation. Figure 39 through Figure 42 confirm that pathway proliferation can only occur when there is more than one cycle in the network, and that this can be confirmed by measuring a cyclicity that is greater than 1.

## 6.5 Conclusion

Groupings of EIPs were made in terms of both their economic status (proposed, existing, or failed) and the level of internal cycling in the network structure (high, medium, basic, and none. When analyzed using selected structural food web metrics commonly used by ecologists for food web analysis, the analyzed groupings create a more complete perspective between each other and biological food webs in terms of their success in being ‘bio-inspired.’ None of the systems, despite their status, successfully match the average values found for biological ecosystems. Based upon these results it is clear that the biological ecosystem, in the sense of the aforementioned structural metrics, has yet to be fully mimicked by industrial networks.

This chapter continues to demonstrate the importance of the structural metric cyclicity for the design and analysis of these industrial systems. Cyclicity, which is used by ecologists to measure the presence and strength of the internal cycling of materials and energy in a system, embodies the major goal for eco-industrial networks. Currently none of the EIPs identified come close to matching median amounts of cycling seen in food webs. Cyclicity is also a measure of the pathway proliferation rate, or the rate that the number of paths increases as path length increases; the higher the cyclicity the greater this rate of increase. This is important because pathway proliferation rate is representative of indirect links in the system, and it has been shown that in food webs when significant cycling was present indirect flows were nearly always found to dominate direct flows.

# CHAPTER 7

# TESTING STRATEGIES TO IMPROVE EIPS: BIGGER IS NOT NECESSARILY BETTER

## 7.1 Research Questions to be Addressed

The 48 EIPs that have been collected show an average and maximum performance well below the average performance characteristic of food webs. The “best” EIP in the collection here has a cyclicity of 3.87 and a linkage density of 3.13 while the average food web in the collection here has a cyclicity of 6.03 and a link density of 7.69, almost twice as large as the two values for the best EIP. One thought to increase the success of EIPs is to look into having EIPs interact with each other, combining two or more synergistic networks to create a larger, and hopefully more successful, synergistic mega-network. Identifying fundamental physical relationships responsible for the correlation between bio-inspired network patterns and environmentally superior industrial network designs and create design guidance there from are two of the goals of this dissertation. In order to move towards the accomplishment of these goals all aspects of the relationships identified need to be investigated: here the size of the network is explored.

## 7.2 Methods: EIP Combos

With a bias for choosing EIPs which ranked low with respect to food webs, EIPs were chosen and grouped together based on shared materials and energy exchanges. Linkages inside each of the EIPs were not modified. All possible links were added between EIPs based on knowledge of what was being exchanged in the original EIP. This results in a maximally connected combination-EIP (i.e. best case scenario for the available information). The realistic exchanges are also noted, which exclude the exchange of water (both wastewater and other water qualities), steam, and electricity as these are not currently economically feasible across the globe. The groupings are be abbreviated as *Combo 1* through *Combo 5* from here on. Ecological metrics were calculated for each of the groups and compared to the values of the individual EIPs in each group and average food web values. The metrics were also calculated for the grouped EIPs before new connections were added to highlight the effect of the new connections.

## 7.3 Results: EIP Combos

### 7.3.1 EIP *Combo 1*: Lubei Industrial Park, Mongstad EIP, Wallingford EIP, and Kymi EIP

The four EIPs in *Combo 1* were paired due to a common use of water, steam, fly ash, wastewater, electricity, hydrogen, carbon dioxide, chlorine, and sodium hydroxide. Lubei Industrial Park, designed to be located in China, is outlined by Mathews and Tan (Mathews and Tan 2011). The Kymi EIP located in Kymenlaakso, Finland is outlined by Sokka et al (Sokka, Pakarinen et al. 2011). The EIP Mongstad located in Mongstad, Norway is outlined by Reap (Reap 2009). The Wallingford EIP is located in Wallingford, Connecticut and is outlined by Reap (Reap 2009). The two EIPs Lubei and Mongstad both have aquaculture as their active agriculture actor. Nine different materials and energy streams were able to be exchanged between the four EIPs, five of which realistically could be exchanged taking into account the distances between the EIPs (locations range from Finland to Connecticut to Norway to China).

Table 21: *Combo 1* EIP made up of Kymi EIP, Lubei Industrial Park, Mongstad EIP, and Wallingford EIP

| **EIP *Combo 1*** | | Active Agriculture Component? | Actors (N) | Links (L) | Predator | Prey | Connectance (C = $L/N^2$) | Linkage Density ($L_D$) | Prey/Predator Ratio ($P_R$) | Specialized Predator Fraction ($P_S$) | Vulnerability (V) | Generalization (G) | Cyclicity ($\lambda_{max}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *23* | Kymi EIP | N | *8* | *14* | *7* | *7* | *0.22* | *1.75* | *1.00* | *0.714* | *2.00* | *2.125* | *1.82* |
| *27* | Lubei Industrial Park | Y | *9* | *17* | *7* | *8* | *0.21* | *1.89* | *1.14* | *0.429* | *2.13* | *2.22* | *0* |
| *29* | Mongstad EIP | Y | *11* | *20* | *10* | *8* | *0.17* | *1.82* | *0.8* | *0.300* | *2.50* | *1.57* | *1.55* |
| *48* | Wallingford EIP | N | *12* | *18* | *11* | *9* | *0.125* | *1.50* | *0.820* | *0.545* | *2.00* | *2.80* | *1* |
| **Combo1 Pre Links Added** | | | *40* | *72* | *35* | *32* | *0.045* | **1.80** | **0.914** | **0.486** | **2.25** | **2.06** | **1.82** |
| **Combo1 Post Links Added** | | | *40* | *169* | *36* | *33* | *0.106* | **4.23** | **0.917** | **0.111** | **5.12** | **4.69** | **4.48** |
| **% change** | | | *0* | *135* | *3* | *3* | *135* | **135** | **0** | **-77** | **128** | **128** | **146** |

### 7.3.2 EIP *Combo 2*: GERIPA, Gladstone, and Montfort

The three EIPs in *Combo 2* were paired due to a common use of soil and other organic wastes, fly ash, and biogas. GERIPA, which stands for Geração de Energia Renovável Integrada á Produção de Alimentos, is an IBS (integrated bio-system) designed for Brazil and is outlined in (Ometto, Ramos et al. 2007, Reap 2009). Gladstone is a proposed addition to an existing EIP in Gladstone, Australia can be found outlined in (Corder 2005, Corder 2008, Reap 2009). The Montfort Boys Town is also an integrated bio-system located in Suva, Fiji and can be found outlined in (Reap 2009).The active agriculture actors in the three EIPs GERIPA, Gladstone, and Monfort include respectively farming and a biodigestor, biomass and fertilizer production, and farming, aquaculture, and fertilizer production. Six different materials and energy streams were able to be exchanged between the three EIPs, four of which realistically could be exchanged taking into account the distances between the EIPs (locations range from Brazil to Australia to Fiji).

Table 22: *Combo 2* EIP is made up of GERIPA IBS, Gladstone, and Montfort IBS.

| **EIP *Combo* 2** | | Active Agriculture Component? | Actors (N) | Links (L) | Predator | Prey | Connectance $(C = L/N^2)$ | Linkage Density $(L_D)$ | Prey/Predator Ratio $(P_R)$ | Specialized Predator Fraction $(P_S)$ | Vulnerability (V) | Generalization (G) | Cyclicity $(\lambda_{max})$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *11* | GERIPA (IBS) | Y | *8* | *15* | *6* | *8* | *0.230* | *1.88* | *1.33* | *0.167* | *1.88* | *1.80* | *1.93* |
| *13* | Gladstone (2008) | Y | *23* | *25* | *13* | *14* | *0.050* | *1.09* | *1.08* | *0.692* | *1.79* | *1.17* | *0* |
| *28* | Monfort Boys Town (IBS) | Y | *9* | *11* | *7* | *7* | *0.140* | *1.22* | *1.00* | *0.571* | *1.57* | *2.43* | *1* |
| **Combo2 Pre Links Added** | | | *40* | *49* | *28* | *26* | *0.031* | **1.23** | **0.929** | **0.607** | **1.88** | **1.75** | **1.93** |
| **Combo2 Post Links Added** | | | *40* | *124* | *32* | *29* | *0.078* | **3.10** | **0.906** | **0.344** | **4.28** | **3.88** | **4.01** |
| **% change** | | | *0* | *153* | *14* | *12* | *153* | **153** | **-2** | **-43** | **127** | **121** | **108** |

### 7.3.3 EIP *Combo 3*: Kymi and Wallingford

The two EIPs in *Combo 3* were taken from *Combo 1* to test the lack of presence of an active agricultural component. Three different materials and energy streams were able to be exchanged between the two EIPs, only one of which realistically could be exchanged taking into account the distance between Finland and Connecticut where the two EIPs are located.

Table 23: The *Combo 3* EIP is made up of Kymi EIP and Wallingford EIP.

| **EIP Combo 3** | | Active Agriculture Component? | Actors (N) | Links (L) | Predator | Prey | Connectance ($C = L/N^2$) | Linkage Density ($L_D$) | Prey/Predator Ratio ($P_R$) | Specialized Predator Fraction ($P_S$) | Vulnerability (V) | Generalization (G) | Cyclicity ($\lambda_{max}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *23* | Kymi EIP | N | *8.0* | *14* | *7* | *7* | *0.22* | *1.75* | *1.00* | *0.714* | *2* | *2.13* | *1.82* |
| *48* | Wallingford EIP | N | *12* | *18* | *11* | *9* | *0.125* | *1.50* | *0.820* | *0.545* | *2* | *2.80* | *1* |
| **Combo3 Pre Links Added** | | | *20* | *34* | *18* | *16* | *0.085* | **1.70** | **0.889** | **0.611** | **2.13** | **1.89** | **1.82** |
| **Combo3 Post Links Added** | | | *20* | *53* | *18* | *16* | *0.133* | **2.65** | **0.889** | **0.333** | **3.31** | **2.94** | **2.81** |
| **% change** | | | *0* | *56* | *0* | *0* | *56* | **56** | **0** | **-45** | **56** | **56** | **55** |

### 7.3.4 EIP *Combo 4*: Brownsville EIP, Burnside EIP, Clark Special Economic Zone, and Kawasaki

The four EIPs in *Combo 4* were paired due to a common use of soil and other organic wastes, waste plastic, used oil and tires, steam, water, and wastewater. The Brownsville EIP was located in Brownsville, TX and can be found outlined in (Martin, Weitz et al. 1996). The Burnside EIP is in Nova Scotia, Canada and can be found outlined in (Cote 2009). The Clark Special Economic Zone was proposed for the Philippines and is outlined in (Reap 2009). The active agriculture actors in the Clark EIP are the result of landscaping, a golf course, a greenhouse, and composting. Seven different materials and energy streams were able to be exchanged between the four EIPs, four of which realistically could be exchanged taking into account the distances between the EIPs (locations range from Texas to Canada to the Philippines to Japan).

Table 24: The *Combo 4* EIP is made up of the Brownsville EIP, Burnside EIP, Clark Special Economic Zone, and Kawasaki.

| **EIP *Combo 4*** | | Active Agriculture Component? | Actors (N) | Links (L) | Predator | Prey | Connectance (C = L/N$^2$) | Linkage Density ($L_D$) | Prey/Predator Ratio ($P_R$) | Specialized Predator Fraction ($P_S$) | Vulnerability (V) | Generalization (G) | Cyclicity ($\lambda_{max}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *4* | Brownsville EIP | N | *16* | *22* | *10* | *12* | *0.086* | *1.38* | *1.2* | *0.400* | *1.83* | *1.14* | *1.41* |
| *5* | Burnside EIP | N | *11* | *20* | *10* | *9* | *0.165* | *1.82* | *0.9* | *0.300* | *2.22* | *2.20* | *2.05* |
| *6* | Clark Special Economic Zone | Y | *20* | *51* | *19* | *17* | *0.128* | *2.55* | *0.895* | *0.263* | *3.00* | *2.00* | *3.34* |
| *21* | Kawasaki | N | *8* | *16* | *8* | *8* | *0.250* | *2.00* | *1.00* | *0.500* | *2.00* | *1.62* | *1.88* |
| **Combo4 Pre Links Added** | | | *55* | *109* | *47* | *46* | *0.036* | **1.98** | **0.979** | **0.340** | **2.37** | **2.32** | **3.34** |
| **Combo4 Post Links Added** | | | *55* | *235* | *47* | *46* | *0.078* | **4.27** | **0.979** | **0.149** | **5.11** | **5.00** | **3.94** |
| **% change** | | | *0* | *116* | *0* | *0* | *116* | **116** | **0** | **-56** | **116** | **116** | **18** |

### 7.3.5 EIP *Combo 5*: Brownsville EIP, Burnside EIP, and Kawasaki (i.e. no agriculture)

The three EIPs in *Combo 5* were taken from *Combo 4* to test the lack of presence of an active agricultural component. Four different materials and energy streams were able to be exchanged between the three EIPs, three of which realistically could be exchanged taking into account the distances between the EIPs (locations range from Texas to Canada to the Japan).

Table 25: The *Combo 5* EIP is made up of the Brownsville EIP, Burnside EIP, and Kawasaki.

| **EIP *Combo 5*** | | | Active Agriculture Component? | Actors ($N$) | Links ($L$) | Predator | Prey | Connectance ($C = L/N^2$) | Linkage Density ($L_D$) | Prey/Predator Ratio ($P_R$) | Specialized Predator Fraction ($P_S$) | Vulnerability ($V$) | Generalization ($G$) | Cyclicity ($\lambda_{max}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *4* | 3B | Brownsville EIP | N | *16* | *22* | *10* | *12* | *0.086* | *1.38* | *1.20* | *0.400* | *1.83* | *1.14* | *1.41* |
| *5* | 2B | Burnside EIP | N | *11* | *20* | *10* | *9* | *0.165* | *1.82* | *0.900* | *0.300* | *2.22* | *2.20* | *2.05* |
| *21* | 2B | Kawasaki | N | *8* | *16* | *8* | *8* | *0.250* | *2.00* | *1.00* | *0.500* | *2.00* | *1.62* | *1.88* |
| **Combo5 Pre Links Added** | | | | *35* | *58* | *28* | *29* | *0.047* | **1.66** | **1.04** | **0.393** | **2.00** | **2.07** | **2.05** |
| **Combo5 Post Links Added** | | | | *35* | *93* | *28* | *29* | *0.076* | **2.66** | **1.04** | **0.321** | **3.21** | **3.32** | **2.34** |
| **% change** | | | | *0* | *60* | *0* | *0* | *60* | **60** | **0** | **-18** | **60** | **60** | **14** |

## 7.4 Discussion

"A system is never the sum of its parts; it's the product of their interactions" Russell Ackoff.

The effect of the additional linkages between EIPs was consistently strongest for the metrics linkage density ($L_D$), generalization ($G$), and vulnerability ($V$). All three of these metrics are influenced by the number of linkages in the network and thus the effect of the addition of linkages is reflected in all of these. Cyclicity ($\lambda_{max}$) was strongly affected in only three of the five groups. *Combo 1* and *Combo 2* saw the biggest increases in cyclicity due to the additional connections made; a 146% and 108% change respectively. Whether or not it is a coincident, these two groupings also had the largest percentage of EIPs with an agricultural component. The additional linkages did not effect, or had very limited effect on the number of predator- or prey-type actors in the system. This is because we could only use companies that already provided preset materials or energy (prey) and could only connect them to companies that already used preset material or energy (predator). The EIPs Brownsville, Kymi, Gladstone 2008, GERIPA, Montfort, and Wallingford all contained a bit of additional information with regards to what they were exchanging and receiving and thus linkages were able to be created making actors which were only prey previously predators and vice versa. Without additional information about the EIPs and their other input and output flows new predator- and prey-type actors could not be designated.

Table 26: Combination EIPs compared against each other and averages for the post 1993 food webs dataset.

| | Cyclicity ($\lambda_{max}$) | Linkage Density ($L_D$) | Prey/Predator Ratio ($P_R$) | Specialized Predator Fraction ($P_S$) | Vulnerability (V) | Generalization (G) | Actors (N) | Links (L) | Predator | Prey | Connectance ($C = L/N^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Food Webs Post 1993 Averages** | **6.03** | **7.69** | **1.13** | **0.100** | **8.82** | **9.69** | *57* | *523* | *47* | *51* | *0.155* |
| **Combo1** | **4.48** | **4.23** | **0.917** | **0.111** | **5.12** | **4.69** | *40* | *169* | *36* | *33* | *0.106* |
| **Combo2** | **4.01** | **3.10** | **0.906** | **0.344** | **4.28** | **3.88** | *40* | *124* | *32* | *29* | *0.078* |
| **Combo3** | **2.81** | **2.65** | **0.889** | **0.333** | **3.31** | **2.94** | *20* | *53* | *18* | *16* | *0.133* |
| **Combo4** | **3.94** | **4.27** | **0.979** | **0.149** | **5.11** | **5.00** | *55* | *235* | *47* | *46* | *0.078* |
| **Combo5** | **2.34** | **2.66** | **1.04** | **0.321** | **3.21** | **3.32** | *35* | *93* | *28* | *29* | *0.076* |

*Combo1* and *Combo 2* both have a drastically higher cyclicity, 4.48 and 4.01 as presented in Table 26, than that seen in each of the individual EIPs components. This

cyclicity is representative of complex and abundant internal cycles forming between the actors. The average cyclicity seen for food webs is 6.03 and the best EIP in the group of 48 in Appendix D had a cyclicity of only 3.87. The cyclicities of the individual EIPs making up each combination ranged from zero, meaning no cycles are present, to less than 2, meaning some complex cycling is present. So by combining EIPs together, more connections were able to be made, resulting in a network with a more complex structure. The metrics linkage density ($L_D$), connectance ($c$), generalization ($G$), and vulnerability ($V$) also showed an increase between the individual EIPs and the combined EIP networks. All four mimicked changes in the number of additional links very closely. For the metrics generalization and vulnerability this was due to the fact that because the information to create new predator- and prey-type actors was not available only the numerators of these metrics changed: the number of links ($L$). The prey to predator ratio ($P_R$) stayed approximately the same for all combination EIPs created for the same reason. Linkage density and connectance only changed by the number of links as well.

The changes between the combined EIPs without additional links added, or where the networks are essentially just added together as is, and the combined EIPs with possible links added may be summarized by just two metrics: linkage density and cyclicity. Linkage density captures the number of species in the system and any changes in the number of linkages. Cyclicity on the other hand captures any changes in the network structure due to how the new or lost linkages interact with the rest of the system. Connectance could be used interchangeably with linkage density as they both capture changes in actors and links. Linkage density is preferably to connectance however in that it does not require systems of similar size if used for comparisons. The metrics prey to predator ratio, generalization, and vulnerability are of interest only if additional information about the system is available so that changes in the behavior of the system actors may be made.

### 7.1.1 Effects of Agriculture in EIPs

The question regarding the impact of agriculture on an EIP success in mimicking ecosystem structure and function is a potentially important question for designers of EIPs. Of the 48 EIPs investigated here 34 had some type of agricultural component and 14 did not. The five (5) combination EIPs made in this chapter investigate possible effects of agriculture in an industry network. *Combo 3* and *Combo 5* in particular were created to test the added value of having an agriculture component, neither of the two groups have an EIP with an agriculture component. Improvements are still seen from the individual EIPs to the larger combined EIP, however not as significant as changes seen for *Combo 1*, *Combo 2,* and *Combo 4*, which all had an agricultural component in one of more of the EIP building blocks. Perhaps the best way to look at the added value of agriculture is between *Combo 1* and *Combo 3* and *Combo 4* and *Combo 5*. The two agriculture EIPs in *Combo 1* bring cyclicity up to 4.48, without these two components cyclicity only reaches 2.81, below that of the best single EIP. The singular EIP with an agriculture component (landscaping, a golf course, a greenhouse, and composting) in *Combo 4* brings the cyclicity for the entire group up to 3.94, without it the cyclicity is 2.34. Some of the benefit of an agriculture component in an EIP has to do with the ability to use a mixture of diverse byproducts, such as organic wastes such as food or paper wastes, animal effluent, compost, and fertilizer for a variety of purposes.

### 7.1.2 Effects of Physical Proximity between EIPs

Some literature points out that the physical proximity of ecosystems is something that industrial networks cannot recreate and therefore any hope for a successful analogy is lost (Husar 1994). While it is true that ecosystems often have a physical proximity that is becoming more uncommon in today’s global economy; species proximity results in low energy expenditures for transportation of materials and energy in addition to relatively short reaction times in the face of perturbations. The energy expenditures of transportation in an industrial setting may not be that distinct from the energy which an animal, especially a migratory animal, must expend to feed for example storks have a system boundary that extends over 12,000 km (van den Bossche 2005). Industrial networks need not be collocated to reap some of the benefits from cyclical interactions that result from mimicking the structure of food webs. In addition to these location independent benefits, constant improvements in infrastructure and transportation are creating more cost effective solutions that once in place can result in minimal energy transfer requirements. A greater distance between networks however does make the exchange of things such as wastewater and steam unrealistic, two materials which are very commonly and successful exchanged between collocated industries. Thus distance should not be a deterrent to the implementation of food web structure and creation of new industrial networks, only recognized such that the best choices as to what is exchanged may be made. Benefits such as longer paths that better use the entirety of a material and the robustness and stability that results from a diverse exchange system in today's global economy do not depend on proximity.

### 7.5 The Value of Information Levels

Figure 43 demonstrates the value of different levels of detail in the information provided by companies to EIP designers. The first two levels should be standard for any claims to be made regarding the success with which an EIP mimic food webs. Many mentions of EIPs in the literature however only include the first level. The combination EIPs created in section 7.3 were only able to be generated to a certain degree as information beyond level 3 was not available.

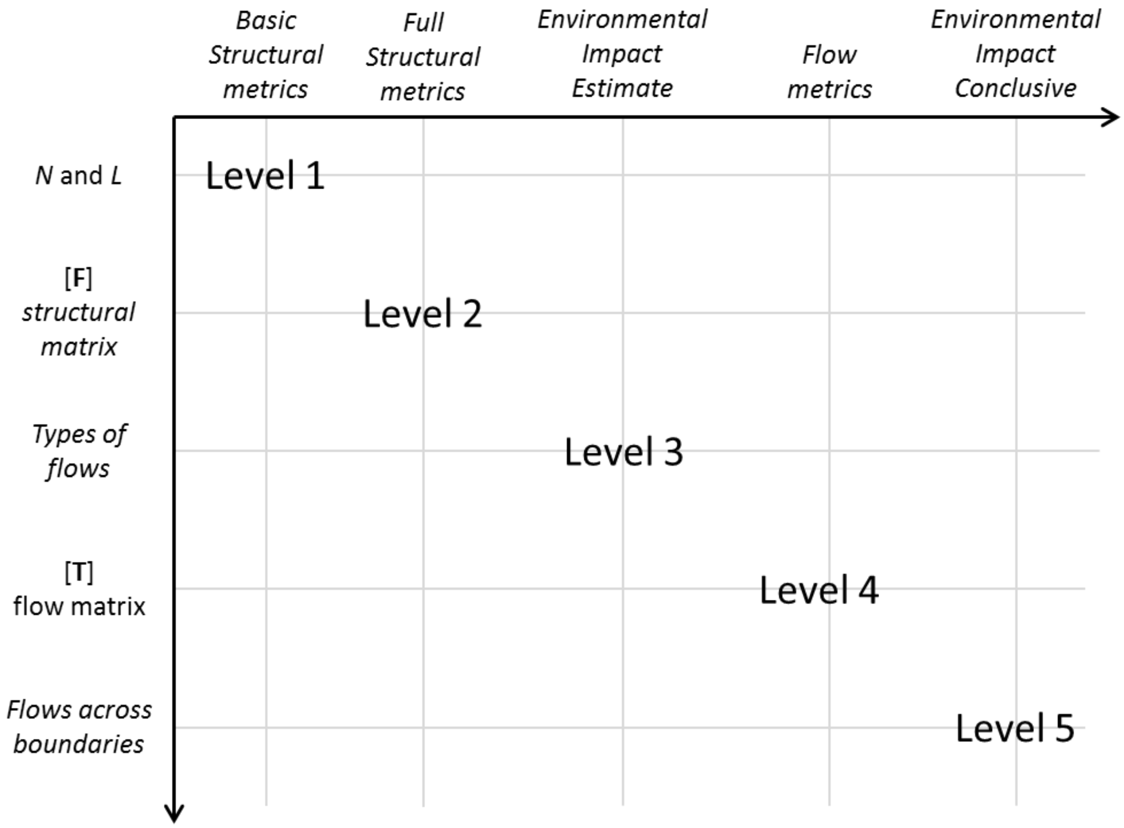


Figure 43: Food web analysis levels and the information they require (vertical axis) and provide (horizontal axis).

*1st Level)* Very basic information: Knowledge of only the number of actors and the number of relationships between actors (links) in the EIP.

- With this the metrics species number, links, linkage density, and connectance can be calculated.

*2nd Level)* One step up from the most basic level of information is: Knowledge of the where the connections are going to and coming from, or which companies are trading with whom.

- With this information the food web matrix can be created and the rest of the structural metrics can be calculated: prey, predators, prey-to-predator ratio, vulnerability, generalization, and cyclicity.

*3rd Level)* The next level of information, we’ll called it medium, is only given on occasion in the current literature for EIPs. This level provides knowledge about what the connections between companies are made of; what types and the quality of the materials and energy being exchanged.

- With this information conclusions can be drawn as to the impact that different types of materials and energy have when they are exchanged. This information also allows for summaries as to the positive environmental impact that results from exchanging rather than disposing or using raw materials may have.

*4th Level)* The next level is beyond what is available for most EIPs in the current literature: knowledge about how much is being exchanged across each link. This allows for an advanced illustration of the EIP in terms of its ability to mimic food webs function, adding to the structural analysis.

- With this information again additional conclusions can be drawn as to the impact of each of the connections. New metrics can be calculated, including a whole host of flow based metrics. These metrics use the ‘strength’ of the flows to determine network properties. With this information accurate environmental impacts can be determined as to the amount of materials and energy saved by creating the exchanges rather than having the flows be solely raw materials and waste.

*5th Level)* The final level of knowledge creates the most advanced analysis of EIPs. This level of knowledge provides information on inputs and outputs that cross system boundaries, or supply and export from and to things outside EIP.

- With this information a complete picture of the EIP can be generated, and with this both structural and flow based food web analyses can be done to fully analyze the EIP. Suggestions can also be made as to possible addition connections between companies and new companies that may be mutually beneficial if added to the EIP. This level of information requires a very high level of transparency though, a level which due to proprietary concerns most companies are not comfortable with providing.

## 7.6 Conclusion

This chapter demonstrates that simply increasing the size of an EIP is not enough to generate positive food web-minded changes. The changes at a minimum must result from additional linkages being added, so reducing the size of a network while increasing links would be more positive than simply adding actors to the system without regard to the potential opportunities for exchanges. This is essentially streamlining or editing for efficiency. It has been noted in ecological literature that there may in fact exist a point where a more streamlined network, essentially a network with less diversity, has negative repercussions in the form of overdependence and reduced robustness to random perturbations.

A hypothesis within ecology is that diversity may be a strong contributor to the stability of a system: when one actor is removed the system may adapt or recover by another actor(s) stepping in to fulfil the supporting role (Korhonen and Snäkin 2005). The natural tendencies for ecosystems as they mature is for the interactions to become more selective, shifting the focus from production towards efficiency (Odum 1969). Mature ecosystems obtain efficiency by way of an increase in use of existing actors, essentially using what is available as completely as possible. This results in the desirable property of a complex structure with an abundance of connections between species (Fath and Halnes 2007).

The efficient use or acquisition amongst species in a food web translates into population increases and a cascading of positive benefits for all species involved (Ulanowicz 1997, Borrett, Fath et al. 2007). The efficient use or acquisition among EIP actors translates into increases in profits and decreased emissions, also positive changes that have widespread effects. Current human designed system tend to resemble young ecosystems rather than mature ones as they are geared towards production often at the expense of efficiency.

Korhonen and Snäkin have addressed the industrial analogy with ecosytem maturaty by creating a 3 type ranking which ranges from immature/newborn systems (type I) to mature-adult systems (type III) (Korhonen and Snäkin 2005).

This chapter also demonstrates the value of different levels of detail in the information provided by companies to EIP designers.The necessity of the first two levels (the basics of number of actors, links, and placement/directionality of the links) has been confirmed, as well as the added value of knowing the identity and quality of what is being exchanged between actors in the system. The added value of the fourth and fifth levels of information are shown in chapters 8 and 9 following.

# CHAPTER 8

# INDUSTRIAL ECOSYSTEMS AND FOOD WEBS: FLOW ANALOGY

## 8.1 Research Questions to be Addressed

In the preceding chapters, structural-ecological analyses of eco-industrial parks have been performed. The next frontier in bio-inspired design of industrial networks is in flow-based analyses through the use of flow metrics and measures from food webs. This has not yet been done for EIPs, therefore everything from basic industry definitions to the analysis process needs to be defined and translated to the industrial context. This chapter addresses the research goal of investigating flow-based analyses of food webs and their application to industrial resource networks. Through the exploration of flow analyses this chapter hopes to answer the following two questions:

1) What value does flow based information for ecological analyses have for industry?
2) What, if any, additional information is provided from flow-based ecological analyses, that is not available from the previous structural analyses?

A better understanding of flow based metrics and their use in industrial networks will also contribute to the larger research goal of creating design guidance for the construction and development of successful EIPs.

## 8.2 A Flow-Based Ecosystem Network Analysis (*ENA*)

The ecological network analyses (ENA) used to complete the structural analyses of food webs in the previous chapters can also be used for flow-based analyses of food webs. Flows in food webs convert the amount of materials or energy exchanged per unit time across the connections between species in a food web. The ability to use flow information to analyze a food web allows ecologists to investigate properties such as ecosystem development, system maturity, and the levels of specialization and redundancy in the system. *Development* in an ecosystem is the movement towards a reduction in the systems dependence on external resources (sustainability is the ultimate goal of development) (Bodini and Bondavalli 2002). *Maturity* level and *ecosystem health* are related to the redundancy or specialization levels of the connections in the system (Mageau, Costanza et al. 1998, Ulanowicz 2009, Bodini 2012). All of these properties can be connected back to the overall robustness of the ecosystem, which is of great concern as system perturbations causing extinction and habitat loss are becoming more common every day. These properties are also all of great interest to industrial resource networks. System robustness is of particular interest to industry. One of the biggest deterrents to investing money and time into new network ideas (such as what must be done for EIPs) is that there is no guarantee against failure. Thus the end results of an ENA using flow information for designing industry networks is both a more robust design and potentially a confidence measure as to the ability of the system to survive in unstable market conditions.

## 8.3 Methods: ENA Using Flow-based Information

The ecological network analyses (ENA) used in the previous structural analyses of food webs can also be used for flow based analyses of ecosystems. A flow based analysis follows four different classes of flow (Ulanowicz and Norden 1990, Bodini and Bondavalli 2002):

1) Inputs that enter across the system boundaries.
2) Flows that move between the actors within the system boundaries.
3) Exports that leave across the system boundaries.
4) Dissipation losses (these are applicable to water and energy flows in particular).

The efficiency of the networks existing connections in moving materials and energy through the system is representative of the specialization in the system. Network efficiency is in direct competition however with network robustness, or protection from random systemic disturbances through a redundancy in connections. Take the hypothetical network of Figure 44, where some commodity must be moved from A to B. Scenario one represented by the dashed line has only one connection moving flow between A and B - the system is highly efficient in meeting this need. A system disturbance that causes this one connection to be damaged or severed would immediately result in the required transport no longer being satisfied. Scenario two has multiple connections of different types moving flow from A to B, represented by the solid paths in Figure 44. This is indicative of a less efficient network, as now multiple connections are doing the job that one connection did in the first scenario. Were a system disturbance to occur in scenario two causing one connection to be damaged, the system would be able to quickly adapt and continue to fulfil the required transport. This adaptation is the reason ecosystems in nature have evolved such that a certain amount of redundancy is present in their structure. Industry however has evolved to keep redundancy to a minimum for the sake profit.

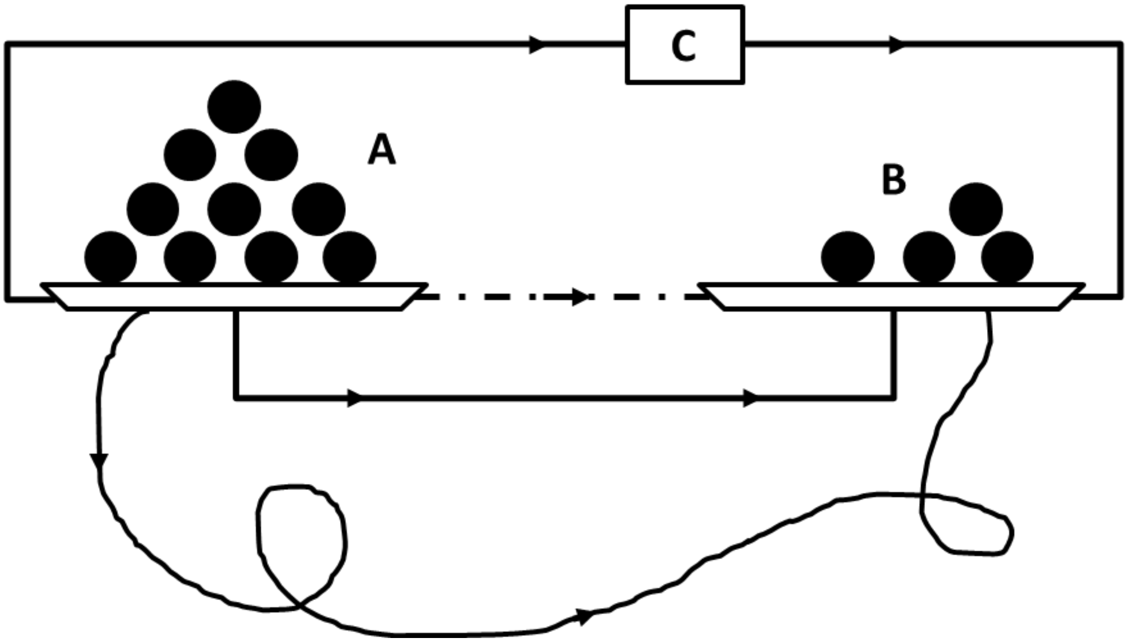


Figure 44: There are many different types of routes and combinations of routes that can be used to meet the goal of transporting some commodity from A to B in a hypothetical network. The dashed line represents an efficient but fragile scenario where only one route is used. The solid lines represent a scenario where multiple routes of different types (direct paths and an indirect path through another actor C) are used, increasing the robustness of the system but at the expense of efficiency.

A package called *enaR* developed by Borrett and Lau (Borrett and Lau 2014), can easily calculate the metrics of interest in an ENA flow analysis. The package is run using the free statistical software called *R* distributed by the R Foundation for Statistical Computing.

### 8.3.1 Ecological Flow Definitions: Matrices and Vectors

Just as a specific setup was required to execute the structural analyses, flow information for food webs must be put into a specific form for an ENA to be applied. The setup is described here in general terms to aid in its application to industrial resource networks.

*Flow Matrix* [**T**]: an ($N$+3) $x$ ($N$+3) matrix, where $N$ is the number of actors in the network, which represents the rate of the internal transfer from the producer or prey actor $i$ to consumer or predator actor $j$ will be represented as $t_{ij}$, or in other words the flow documented is from row to column. The row to column orientation of this matrix follows the practice of Ulanowicz and his followers (*enaR* as designed by Borrett and Lau for example) (Ulanowicz 2004, Borrett and Lau 2014). It should be noted here that Patten and his followers use the reverse orientation in their analyses, setting the flow as from columns to rows in the [**T**] matrix. The Ulanowicz practice is adopted here as this is the dominant method in ecological network analytics (Ulanowicz 1986, Ulanowicz and Norden 1990, Ulanowicz 2004, Borrett and Lau 2013). The matrix is illustrated in Figure 45 adapted from (Scotti, Bondavalli et al. 2009).

- Node *0* is the source of input from outside the system boundaries.
- Nodes *1* to *N* are the internal system actors.
- Node *N+1* is the receiver of usable medium produced, outside the system.
- Node *N+2* is the sink of medium dissipated (medium that is no longer useful).

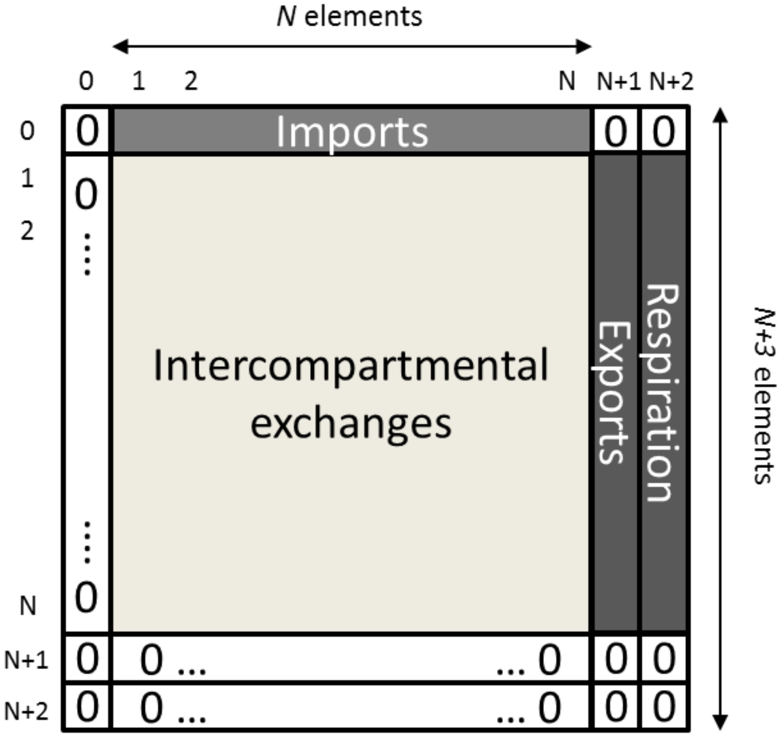


Figure 45: A squared (*N*+3) x (*N*+3) flow matrix where *N* is the number of species represented in the food web, the zeroth row/column entry represents imports to the system across the systems boundaries, the *N*+1 row/column entry represents exports across the system boundaries, and the *N*+2 row/column entries represent respiration or dissipation to the surroundings. *Figure adapted from* (Scotti, Bondavalli et al. 2009).

An energy or mass balance can be done on the components of the **T** matrix, represented by equations 22 and 23. The vector *X* is the rate of inputs to *i* coming from outside the system – row 0 in Figure 45. This is what Ulanowicz calls the 1st class of flows in an ecosystem (Bodini and Bondavalli 2002, Ulanowicz 2004). The vector *E* is the rate of loss of useful medium from node *i* to the outside world - column (*N*+1) in Figure 45. This is also called the 3rd class of flows in an ecosystem (Bodini and Bondavalli 2002). The vector *R* is dissipation from node *i* - column (*N*+2) in Figure 45. This is known as the 4th class of flows in an ecosystem (Bodini and Bondavalli 2002). Some literature uses a vector *Y* that represents *all* exports from the system, a combination of the output vector *E* and the respiration/dissipation vector *R* (Patten 1978). Two additional vectors are sometimes seen in the literature, regarding loss when forcing an energy balance and storage. The vector $G$ is the instantaneous storage of biomass used for an artificial mass/energy balance. The vector $L$ is the instantaneous loss of biomass used for an artificial mass/energy balance.

$$\bar{X} + \sum_{j=1}^{n} t_{ij} = \sum_{i=1}^{n} t_{ij} + \bar{E} + \bar{R} \tag{22}$$

$$\bar{X} + \bar{G} + \sum_{j=1}^{n} t_{ij} = \sum_{i=1}^{n} t_{ij} + \bar{L} + \bar{E} + \bar{R} \tag{23}$$

*Fractional Flow Matrix* [**G**]: an ($N$+3) $x$ ($N$+3) matrix of partial "feeding" coefficients, where the element $g_{ij}$ represents the fraction of the total input to $j$ that comes directly from $i$. The entries in [**G**] are non-dimensional (Fath and Patten 1999). This matrix is created by dividing each component in any row of [**T**] by it's the sum of the corresponding column in [**T**] (Ulanowicz 1986). This matrix is also found in the literature as [**F**] (Bodini and Bondavalli 2002) (not to be confused with the food web matrix labeled [**F**] as used in this dissertation). The inverse of [**G**] is used by Reap and Bailey and labeled [**Q**] (Bailey 2000, Reap 2009).

### 8.3.2 Ecological Flow Definitions: Metrics

The metrics discussed here were all originally applied to ecosystems by Ulanowicz and Patten, but have also been investigated by other groups of researchers who have added to the discussion (Finn 1976, Patten 1978, Ulanowicz 1986, Ulanowicz and Norden 1990, Graedel, van Beers et al. 2005, Bodini 2012, Borrett 2013, Borrett and Lau 2013, Kharrazi, Rovenskaya et al. 2013). These metrics allow for the investigation of properties such as ecosystem development, system maturity, and the quantification of the levels of specialization and redundancy in the system. The intent is to apply the following metrics to EIPs as flow information becomes publically available. Until it this happens, these metrics are applied to the economic, resource, and trade networks for which flow information is available. This creates an understanding of the behavior of these metrics in industrial and engineering terms, setting the stage for their use in EIPs.

*Total System Throughput* (*TSTp*): The sum of all flows in an ecosystem. *TSTp* quantifies the medium processed by system. It is a measure of size or level of activity (similar to GNP, which estimates the overall economic activity of a nation) (Ulanowicz 2000, Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012). *TSTp* is thought to be a more stable metric than looking at production alone and is sensitive to the number of components in the system (Finn 1976). *TSTp* is also referred to as *T* in the literature (Ulanowicz 2000).

$$TSTp = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \tag{24}$$

*Average Mutual Information* (*AMI*) also known as *Average Mutual Constraint* (*AMC or A*): the degree of specialization in the system or the amount of constraints on the materials and or energy flow. *AMI* estimates how strictly the flow is constrained. *AMI* has been suggested as being indicative for the developmental status, or level of system maturity, of the ecosystem. *AMI* has a lower bound of zero, representing a system with no constraints on the flow and highly redundant pathways, and a maximum signifying that the flow is maximally constrained (i.e. a few efficient routes exist with lower cost of maintenance of system) (Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012). Average mutual information is also known as *average mutual constraint* and abbreviated as *AMC* or *I* in the literature (Ulanowicz and Norden 1990, Ulanowicz 2000). One should note that when calculating *AMI*, the scaling constant *k* is usually set to a value of one by ecologists (Ulanowicz 2004).

$$AMI = -k \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} \frac{t_{ij}}{TSTp} \cdot log_2 \left[ \frac{t_{ij} \cdot TSTp}{\left(\sum_{j=0}^{N+2} t_{ij}\right)\left(\sum_{i=0}^{N+2} t_{ij}\right)} \right] \tag{25}$$

*System Ascendency* (*ASC*): Choosing the scaling factor *k* in the calculation for *AMI* to be equal to the total system throughput (*k* =*TSTp* in equation 26) allows one to arrive at system ascendency, attaching physical units to the information index (Ulanowicz 2004). System ascendency measures the amount of medium that an ecosystem distributes in an efficient way, providing a single measure of growth and development (or activity and organization) inherent in the system (Ulanowicz 2000, Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012). *ASC* is dependent on the size of the system (extensive) by way of tue multiplier *TSTp*. *TSTp* is variable between systems and so it is difficult to use ASC as a comparison between systems without adjusting for *TSTp* (Mueller and Leaupelt 1996), which may vary anywhere from $10^3$ to $10^5$ for the networks investigated here. Higher values for ascendency represent a food web with more trophic specialists, increased cycling, and higher efficiency, while lower values for ascendency represent a more generalist-based food web, decreased cycling, and lower transfer efficiencies. Studying the equation for *ASC* one may see that the scenario where the *log2* of zero must be calculated is likely to arise. Special treatment for this case, when $t_{ij}$ is zero is required: the partial *ASC* value ($\mathbf{ASC}[ij]$) is set to zero rather than computing the *log2* of zero. The final ascendency value is the result of adding all of the partial values, thus the zeroes disappear. Borrett and Lau's *enaR* package (Borrett and Lau 2013) uses this treatment of the *log2* of zero and the results have been confirmed using Ulanowicz's *Netwrk* program (Ulanowicz, Mason et al. 2007). System ascendency can also be found abbreviated as *A* in the literature (Ulanowicz 2000).

$$ASC = AMI \cdot TSTp \tag{26}$$

*Development Capacity* (*DC*): Choosing the scaling factor *k* in the calculation for the Shannon Index, *H*, to be equal to the total system throughput (*k* =*TSTp* in equation 24) allows one to arrive at development capacity Following suit for *ASC*, using *TSTp* gives the diversity index physical units (Ulanowicz 2004). Development capacity represents the maximum potential that a system has at its disposal to achieve further improvements, and is an upper bound for *ASC* (Bodini, Bondavalli et al. 2012). *DC* represents the development or evolution potential of the system and is sometimes used as an alternative measurement of the complexity of an ecosystem. *DC* is dependent on the amount of medium available (Bodini and Bondavalli 2002). Development capacity is also referred to as *capacity* and abbreviated as *C* in the literature (Ulanowicz 2000).

$$DC = -1 \cdot \sum_{i=0}^{N+2} \left[ \left( \sum_{j=0}^{N+2} t_{ij} \right) \cdot log_2 \left( \sum_{j=0}^{N+2} t_{ij} \right) \right] \tag{27}$$

$$DC \geq ASC \geq 0$$

*Total System Overhead* (*TSO*): *TSO* pertains to redundant flows in the network and might be an indicator as to the point of optimality between flexibility and efficiency (Ulanowicz 2009, Bodini, Bondavalli et al. 2012). If a systems ascendency is greater than its overhead (*ASC* > *TSO*) then it may be inferred that the system is more evolved than a system that is characterized by the reverse situation (Kharrazi, Rovenskaya et al. 2013). Total system overhead is also referred to as *system overhead* and abbreviated as *Φ* in some literature (Ulanowicz 2000). The sum of *TSO* and *ASC* is the maximum evolutionary potential a system has and is equal to *DC*.

$$TSO = DC - ASC \tag{28}$$

*Cycling Index* (*CI*) or *Finn Cycling Index* (*FCI*): The cycling index is a dimensionless number that accounts for percentage of all fluxes generated by cycling, or the fraction of total activity in the system that is devoted to cycling (Finn 1976, Bodini and Bondavalli 2002, Allesina and Ulanowicz 2004). The metrics was originally developed by Jack Finn in 1976 (Finn 1976). In other words, *CI* is a measure of how much further a system input will travel due to cycling as opposed to a straight path. *CI* differs from cyclicity, also a quantifier of cycling in ecosystems, in that it uses flow magnitude whereas cyclicity uses flow structure. *CI* is not sensitive to the number of actors in the system (Finn 1976) making it a useful metric for comparisons between different types of networks. A cycling index of zero represents a heavy dependence on external resources or in terms of an industrial network no recycling in the system.

$$TST_C = \sum_{j=1}^{n} \left( \frac{t_{jj} - 1}{t_{jj}} \right) T_j \tag{29}$$

$$CI = \frac{TST_C}{TST_f} \tag{30}$$

*Mean Path Length* (*MPL*) also known as *Average Path Length* (*APL*): The mean path length is representative of the number of actors “visited” by a material or energy flow (Finn 1976, Bailey, Bras et al. 2005). Each inflow $X$ and outflow $E$ has its own individual path length that is the average number of actors visited by the respective flow before exiting the system. The mean path length of the entire system is the sum of the inflow or outflow path lengths weighted by the relative size of each respective flow. The equation for *MPL* is shown in equation 31 below, where $\sum x_i$ is the sum of inflows to the system (flows that cross system boundaries into the system).

$$MPL = \frac{TSTf}{\sum x_i} \tag{31}$$

*Robustness* (*R*): First proposed by Ulanowicz, robustness measures the relationship between *ASC* and *DC* (Ulanowicz), or the organizational constraints in the system vs redundancy, normalizing the systems “degree of order” (Fath 2014). Robustness is zero when the ratio of *ASC* to *DC* is equal to one, and approaches zero as (*ASC*/*DC*) approaches zero. Plotting the ratio *ASC*/*DC* against *R* shows a peak that has been termed the “window of vitality” (Ulanowicz, Holt et al. 2014). Ecologists hypothesize that there is an optimal balance between redundancy in the system and the efficiency, or constraints on the movement of flows in the system, at this peak for those systems where there is a potential for disturbances (Ulanowicz 2009, Fath). Nature has been documented reaching a redundancy in flows of up to 25% (Bodini

2012), in industry however redundancy is generally kept to a minimum to reduce system costs, resulting in a high dependence on imports. Ulanowicz addressed the robustness of 48 ecosystem in terms of the ratio *ASC*/*DC* (Ulanowicz 2009).

$$R = -k\left(\frac{ASC}{DC}\right)\log_2\left(\frac{ASC}{DC}\right) \tag{32}$$

### 8.4 Flow Analyses and Comparisons of Eco-Industrial Parks and Food Webs

The flow-based metrics *AMI*, *ASC*, *DC*, *TSO*, and *TST* have not been previously investigated for EIPs and therefore a precedent does not exist for their application to industrial systems. The value of some of these metrics for EIPs can be speculated using published metrics for economic networks (Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012). We hypothesized *DC* will be very high and *ASC* will be low for EIPs in comparison to FWs. Studying the equations presented here, *CI* and *AMI* are normalized by the amount of flow processed by the system (*TSTp*) and *MPL* is normalized in terms of system imports. Chapter 9 will show that when applied to an EIP, these dimensional metrics are orders of magnitude greater than food web medians. This is not necessarily good or bad, it is an artifact of the fact that different networks may operate at different scales. The dimensional metrics (*ASC*, *DC*, and *TSO*) as a result of this scale difference do not offer much in the way of comparisons between networks that operate at different scales (as is the case between EIPs and FWs), therefore this work will focus on the use of the nondimensional metrics (metrics that have been normalized for flow volumes).

There are a few examples in the literature of eco-industrial parks that have flow based information available. Most of the examples have only partial flow data published, which unfortunately does not enable an accurate flow analysis to be done on the system, which needs flow information for all the described linkages in the system and ideally for the system imports and exports as well.

Table 27 lists twelve EIPs with some amount of flow data available and the literature where the data may be found. The Shuozhou EIP in China (#5 in Table 27) has extremely detailed flow information available by Wang *et al*. (Wang, Zhang et al. 2005) however no information regarding the structure of the flows exists and so the information cannot be used. The authors were contacted to try and obtain the structural information necessary, unfortunately no response was received.

Table 28 lists three industrial networks with complete flow based information available. The networks in Table 28 are not eco-industrial parks however they can add to the discussion on the relevance of flow based metrics in an industrial setting. This is especially important since flow metrics can currently be applied to so few EIPs.

Table 27: EIPs with full and partial flow data in the literature.

| **EIP** | | **Data Source** | **Data Defined** |
|---|---|---|---|
| *1* | Lower Mississippi Corridor, USA | (Xu, Indala et al. 2005, Singh, Lou et al. 2007, Reap 2009) | *Full (water)* |
| *2* | Carpet Recycling, Atlanta, GA, USA | (Bailey 2000, Reap 2009) | *Full (carpet)* |
| *3* | Kalundborg, Denmark (data from 2002) | (Jacobson 2006) | *Full( water)* |
| *4* | Kawasaki Eco-town, Japan | (van Berkel 2009, Hashimoto, Fujita et al. 2010, Mathews and Tan 2011) | *Partial* |
| *5* | Shuozhou EIP: Shuozhou, China | (Wang, Zhang et al. 2005) | *Partial (numerical data, but no documentation of network structure)* |
| *6* | Gladstone, Australia | (van Beers, Corder et al. 2007) | *Partial (summary of possible opportunities)* |
| *7* | Pingdingshan Coal Mining Group (Pingmei), China | (Mathews and Tan 2011) | *Partial (6/8)* |
| *8* | Lubei Chemical Group Industrial Park: Wudi, Shandong Province, China | (Mathews and Tan 2011) | *Partial (7/21)* |

Table 27 continued: EIPs with full and partial flow data in the literature.

| EIP | | Data Source | Data Defined |
|---|---|---|---|
| *9* | Tianjin Economic Development Area, China | (Mathews and Tan 2011) | *Partial (9/16)* |
| *10* | Guitang Sugarcane Eco-Industrial Park Project, China | (Mathews and Tan 2011) | *Partial (6/16)* |
| *11* | Kwinana, Australia | (van Beers, Corder et al. 2007, Mathews and Tan 2011) | *Partial (3/many)* |
| 12 | AES Thames | (Becker, Minick et al. 1997) | *Partial* |

Table 28: Industrial networks with partial or full flow data in the literature (non-EIPs).

| | Industrial Network | Data Source | Data Defined |
|---|---|---|---|
| *1* | World Zinc Market (made up of smaller networks at the country and regional level) | (Graedel, Bertram et al. 2005, Graedel, van Beers et al. 2005, Reck, Bertram et al. 2006) | *Full (Zn)* |
| *2* | Water Usage Network for 3 cities in Northern Italy | (Bodini and Bondavalli 2002, Bodini 2012, Bodini, Bondavalli et al. 2012) | *Full (water)* |
| *3* | Six economic resource networks | (Kharrazi, Rovenskaya et al. 2013) | *Full*<br>*(U.S. dollars)* |

The first two EIPs in Table 27 and the three networks in Table 28 have had some amount of flow based analysis applied to them. The completed analyses are explored further and expanded upon in section 8.4.1 following.

### 8.4.1 Investigation of and Expansion on Existing Flow Based Analyses of Industrial Networks

The flow-based metrics *AMI*, *ASC*, *DC*, *TSO*, and *TST* have not been previously investigated for EIPs and therefore a precedent does not exist for their application to industrial systems. Flow-information for EIPs is also very difficult to obtain. As a result five industrial networks that have flow-information available in the literature are investigated to begin to build a hypothesis for the potential of these metrics as industry design guidelines.

#### 8.4.1.1 The Lower Mississippi Corridor, United States

The eco-industrial park redesign of an agro-chemical complex in the Lower Mississippi River Corridor was initially proposed by Singh et al. and focused on the carbon dioxide flows in the network (Singh, Lou et al. 2007). The success of the redesign in imitating FWs was further investigated by Reap and found to fall far short of ecological goal values for the flow based metrics cycling index (*CI*) and mean path length (*MPL*) (Reap 2009). The results of this analysis used the eco-metrics to show that for both the original industrial network as well as the EIP redesign linear flows dominated the structural makeup of the networks. The improvements made to the original design in the supposed vein of ecological networks resulted in a meager 0.4% increase in the mean path length in the system and an almost 50% decrease in the fraction of materials in the network that are cycled, a number that was already low to begin with. Reap attributed the decrease in the cycling in the system to a loss of a benzene recycling loop and concluded that the redesign failed to mimic the flows in biological systems. The overall “EIP” redesign was found to result in an increase in fossil fuel usage and human health and smog impacts by the original designers (Singh, Lou et al. 2007). The apparent failure of biologically-inspired network design to increase performance of the system is actually a failure to implement network structures that enhance cycling in ecological systems.

#### 8.4.1.2 Six Economic Resource Trade Networks (non-EIPs)

Kharrazi et al. investigated the robustness (*R* calculated from equation 33) for six economic networks in terms of the balance between efficiency and redundancy (*ASC*/*DC* calculated from equations 27 and 28) in the system (Kharrazi, Rovenskaya et al. 2013). The six economic networks include: 1) A virtual water trade network encompassing 227 nations, with the volume of water (measured in liters) needed to produce 58 commodities derived from 6 major cereals. 2) An oil trade network of bilateral crude petroleum trade in U.S. dollars. 3) A global commodity trade network encompassing 197 nations with flows documented in U.S. dollars. 4) An OECD-BRIC commodity trade network documented in U.S. dollars. 5) An OECD-BRIC foreign direct investment network documented in U.S. dollars. 6) An iron and steel trade network covering 199 nations documented in U.S. dollars.

#### 8.4.1.3 Three Water Flow Networks (non-EIPs) in Northern Italy

Bodini *et al*. investigate the water flow networks for three municipalities in northern Italy (Bodini, Bondavalli et al. 2012). The networks, the cities of Albareto, Sarmato, and Ravenna, are defined by their administrative boundaries and aggregated such that the networks had 9, 10, and 11 actors respectively. Water flows in [$m^3$/year] were identified for each actor as water flowing from outside the system boundaries (the $\vec{X}$import vector), water flowing within the system boundaries (the inter-compartmental exchanges in the **T** matrix), and water still of value and of no value flowing out across the system boundaries (the $\vec{E}$ export and the $\vec{R}$ dissipation vector respectively). The water network of each municipality was then modified by the authors with the goal of fostering sustainability, defined as reducing resource consumption. This was done by removing leakages and lengthening the pathways along which water traveled before it was discarded.

#### 8.4.1.4 World Zinc Market (non-EIP)

Graedel *et al*. compiled a comprehensive data collection of the flows of zinc from 1994 from 54 countries around the world, building a global anthropogenic zinc network (Graedel, van Beers et al. 2005). The network aggregated the interacting parties into four actors: production, fabrication & manufacturing, use, and waste management. Imports and exports to and from the network across the network boundaries were also documented. The group processed the large dataset using a number of non-ecological flow-based metrics. Metrics included efficiency, recycling, accumulation, reprocessing, landfilling, and scrap ratios. No strictly-ecological flow-based metrics were calculated by Graedel *et al*. The authors detailed knowledge of the quality of zinc flowing at each stage in the network allowed for flow ratios at different stages of the zinc life cycle to be calculated.

#### 8.4.1.5 A Carpet Recycling Network in Atlanta, GA

A carpet recycling network in Atlanta, GA, USA was used to test for a possible correlation between a traditional profit-based flow optimization to a bio-inspired flow optimization (Reap 2009). The model consists of a carpet manufacturing facility, landfills, reuse and recycling facilities, and 13 counties which consume and or store carpet. Of the possible flows in the system, those representing flows of carpet for recycling and reuse were singled out as design variables. The bio-inspired model used 9 equally weighted food web metrics (7 structural metrics and two flow-based metrics – *CI* and *MPL*) to optimize the carpet flows. The structural metrics used were linkage density, prey to predator ratio, fraction specialized predator, generalization, vulnerability, connectance (calculated with cannibalism), and cyclicity. This was compared against a traditional optimization model. The model minimized costs and emissions. The costs were due to material, labor, and energy. Emissions originated from the manufacturing, cleaning, the generation of electricity and natural gas, and transportation. The results of the investigation showed that the carpet recycling network designed to mimic food webs positively correlated with standard cost- and emissions-minimizing designs, with an $R^2$ value of 0.96 as seen in Figure 7, reprinted here as Figure 46 for the readers convenience. The interesting results was that the biologically inspired design, while providing an optimized cost and emissions solution, did so using a unique network structure. It is believed that this unique structure could provide inherent network robustness and stability, aspects that are not considered by conventional industry optimization models  (Reap 2009). This network model is considered in depth in chapter 9 due to this very interesting conclusion.

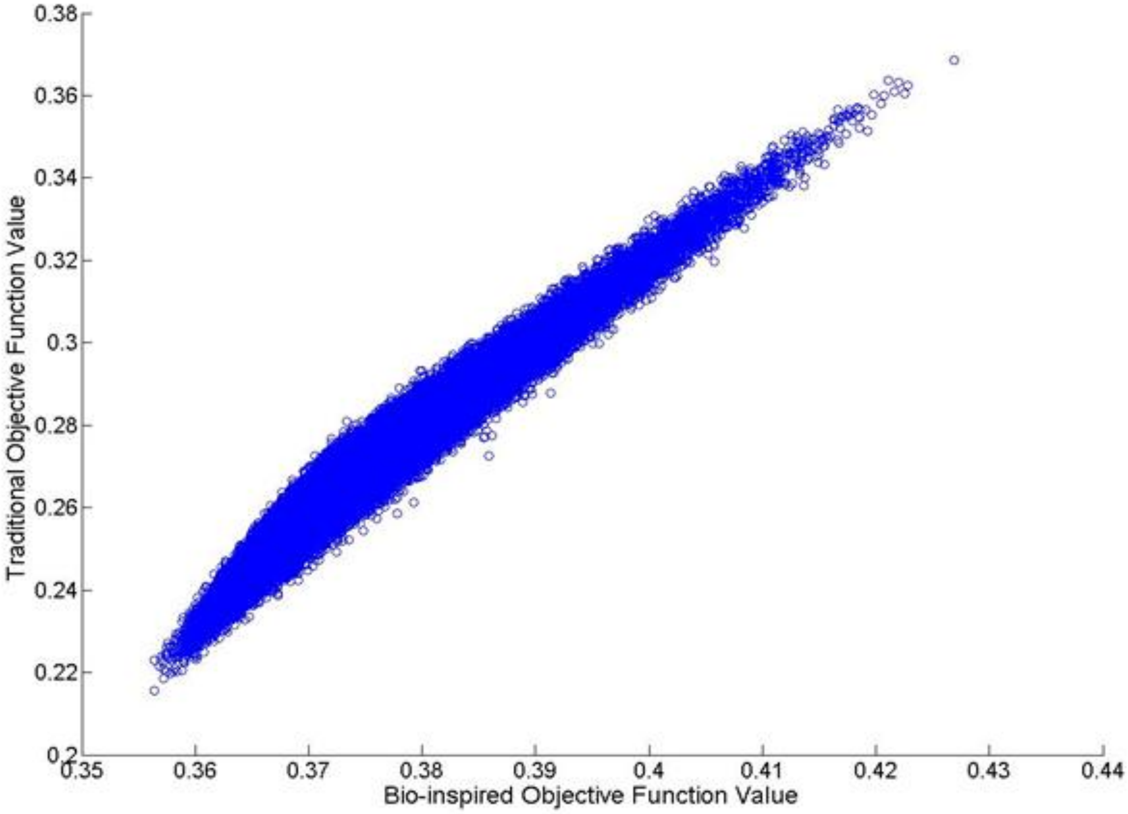


Figure 46: Traditional vs. Bio-Inspired Objective Function Values for 100,000 Randomly Generated Carpet Tile Recycling Network Designs. *Figure from* (Reap 2009, deCharon 2013).

## 8.5 Flow Analysis Results for Select Industrial Networks

### 8.5.1 Results for the Six Economic Resource Trade Networks

Values of *R* were originally calculated by Kharrazi *et al*. using a constant multiplier (*k*) value of 0.7 (Kharrazi, Rovenskaya et al.). The goal here was to compare robustness values of industrial networks to robustness values of food webs. The food web values were calculated using the *enaR* program developed by Borrett and Lau (Borrett and Lau 2013). This program, as well as most other food web analyses, uses a *k* value of one and so *R* was recalculated here for the six economic networks to adjust for this change. The updated values are shown in Table 29 below. Unfortunately no detailed flow information was provided in the original analysis other than these two measures and so additional food web metrics were unable to be calculated.

Table 29: The average degrees of order (*ASC*/*DC*) and corresponding levels of robustness (*R*) for six economic resource trade flow networks originally investigated by Kharrazi *et al*. (Kharrazi, Rovenskaya et al. 2013). The original data has been modified with a change in the constant multiplier *k*, from 0.7 as used in the original article to a value of one.

| | ***ASC/DC*** | ***R*** *(k=1)* |
|---|---|---|
| Virtual Water (1896-2001) | *0.181* | *0.441* |
| Oil (2007-2011) | *0.199* | *0.459* |
| Global Commodity (1962-2010) | *0.092* | *0.317* |
| OECD-BRIC Commodity (1988-2010) | *0.086* | *0.301* |
| OECD-BRIC FDI (1985-2009) | *0.129* | *0.376* |
| Iron and Steel (1962-2011) | *0.127* | *0.374* |
| Virtual Water (1896-2001) | *0.181* | *0.441* |

### 8.5.2 Results for the Three Water Flow Networks in Northern Italy

Bodini *et al*. originally calculated four flow metrics from food webs for three Italian water flow networks: *TSTp*, *DC, ASC*, and *TSO* (as well as variations on *TSO*). These four metrics are outlined in section 8.3.2. The four originally investigated metrics as well as additional flow metrics are calculated and recalculated using the equations outlined in section 8.3.2, with the results shown in Table 30. The flow matrices used to perform the calculations are all located in Appendix F Table F100 through Table F105. Since the information was available, structural food web metrics from section 3.3.2 were also calculated for the three water flow networks and their variations. These are listed in Table 31.

Table 30: Ecological flow information metrics calculated for the water flow networks of three municipalities in northern Italy as collected by Bodini *et al*. (Bodini, Bondavalli et al. 2012). The metrics were calculated using the enaR program (Borrett and Lau 2013). ORIG - The present state of the network at the time of the publication of the reference paper. MOD - Network as modified in the referenced work by Bodini *et al*.

| Metrics | **Albareto** | | **Saramato** | | **Ravenna** | |
|---|---|---|---|---|---|---|
| | **ORIG** | **MOD** | **ORIG** | **MOD** | **ORIG** | **MOD** |
| ***CI*** | *0* | *0* | *0* | *0.002* | *0* | *0.010* |
| ***MPL*** | *1.18* | *1.17* | *1.69* | *1.74* | *1.63* | *2.16* |
| ***AMI (k=1)*** | *1.14* | *1.11* | *1.88* | *1.87* | *1.93* | *2.03* |
| ***TSTp*** | *4.60E+07* | *4.50E+07* | *4.83E+07* | *4.03E+07* | *1.46E+09* | *2.00E+09* |
| ***ASC*** | *8.50E+07* | *8.35E+07* | *7.68E+07* | *6.35E+07* | *2.44E+09* | *2.93E+09* |
| ***DC*** | *9.68E+07* | *9.25E+07* | *1.44E+08* | *1.18E+08* | *4.72E+09* | *5.95E+09* |
| ***TSO*** | *2.02E+08* | *1.92E+08* | *2.59E+08* | *2.05E+08* | *7.74E+09* | *9.49E+09* |
| ***ASC/DC*** | *1.06E+08* | *9.91E+07* | *1.15E+08* | *8.60E+07* | *3.03E+09* | *3.54E+09* |
| ***R*** | *0.478* | *0.483* | *0.557* | *0.579* | *0.609* | *0.627* |

Table 31: Ecological structural information metrics calculated for the water flow networks of three municipalities in northern Italy as collected by Bodini et al. (Bodini, Bondavalli et al. 2012). The metrics were calculated using the *enaR* program (Borrett and Lau 2013). *ORIG* - The present state of the network at the time of the publication of the reference paper. *MOD* - Network as modified in the referenced work by Bodini *et al*.

| Metrics | **Albareto** | | **Saramato** | | **Ravenna** | |
|---|---|---|---|---|---|---|
| | **ORIG** | **MOD** | **ORIG** | **MOD** | **ORIG** | **MOD** |
| ***N*** | *9* | *9* | *10* | *10* | *11* | *11* |
| ***L*** | *14* | *14* | *17* | *17* | *18* | *19* |
| ***Ld*** | *1.56* | *1.56* | *1.70* | *1.70* | *1.64* | *1.73* |
| ***Prey*** | *8* | *8* | *8* | *8* | *10* | *10* |
| ***Predator*** | *6* | *6* | *8* | *8* | *8* | *8* |
| ***Pr*** | *1.33* | *1.33* | *1* | *1* | *1.25* | *1.25* |
| ***Specialized Predators*** | *2* | *2* | *4* | *4* | *3* | *3* |
| ***Ps*** | *0.333* | *0.333* | *0.5* | *0.5* | *0.375* | *0.375* |
| ***G*** | *2.33* | *2.33* | *2.13* | *2.13* | *2.25* | *2.38* |
| ***V*** | *1.75* | *1.75* | *2.13* | *2.13* | *1.8* | *1.9* |
| ***c*** | *0.173* | *0.173* | *0.170* | *0.170* | *0.149* | *0.157* |

Figure 47and Figure 48 visualize the changes in each of the three water-usage networks outlined in Table 30 and Table 31, and compare them to median values for the post 1993 food web dataset. The modifications made in each of the networks produced no large measurable changes in any of the metrics, other than the introduction of internal cycling in Saramato and the introduction of complex internal cycling in Ravenna. All of the networks still lack the complexity and characteristic of food webs as measured by the metrics chosen here. Generalization and vulnerability also show an especially marked difference between the water networks and the food webs. The metrics for which the water use networks most closely resembled the food webs were *R* and the measure of the degree of order in the system (the ratio *ASC*/*DC*).

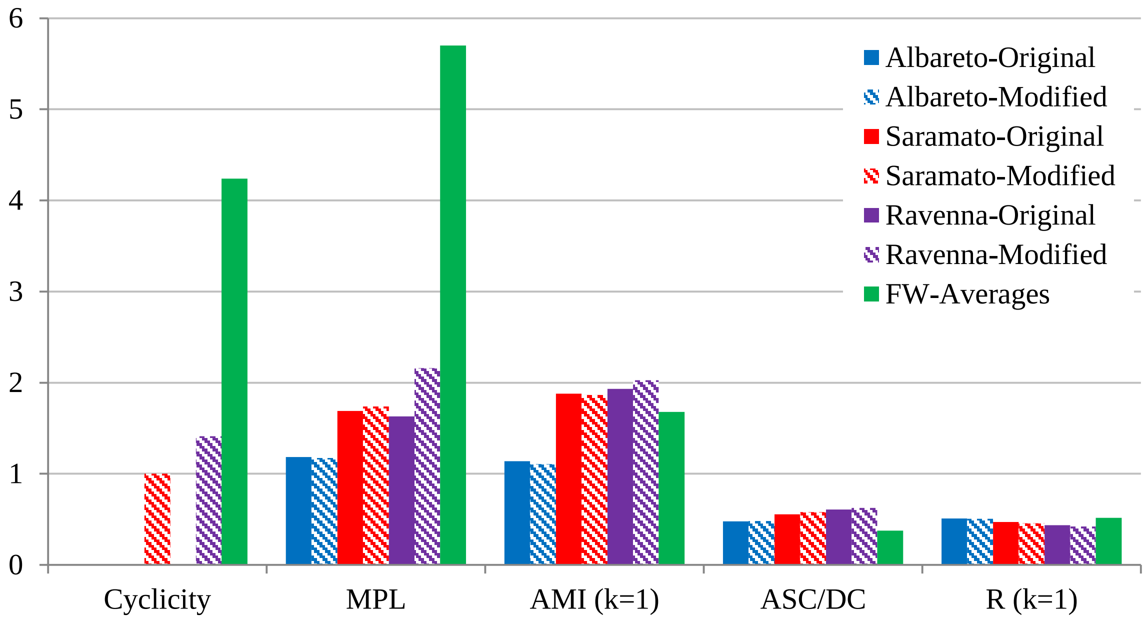


Figure 47: Dimensionless flow metrics for the original and modified water-use networks from Bodini *et al.* (Bodini, Bondavalli et al. 2012) as compared to post-1993 food web medians. *MPL* stands for Mean Path Length, *AMI* for average mutual information, *ASC/DC* is the system ascendency divided by development capacity, and *R* is the system robustness.

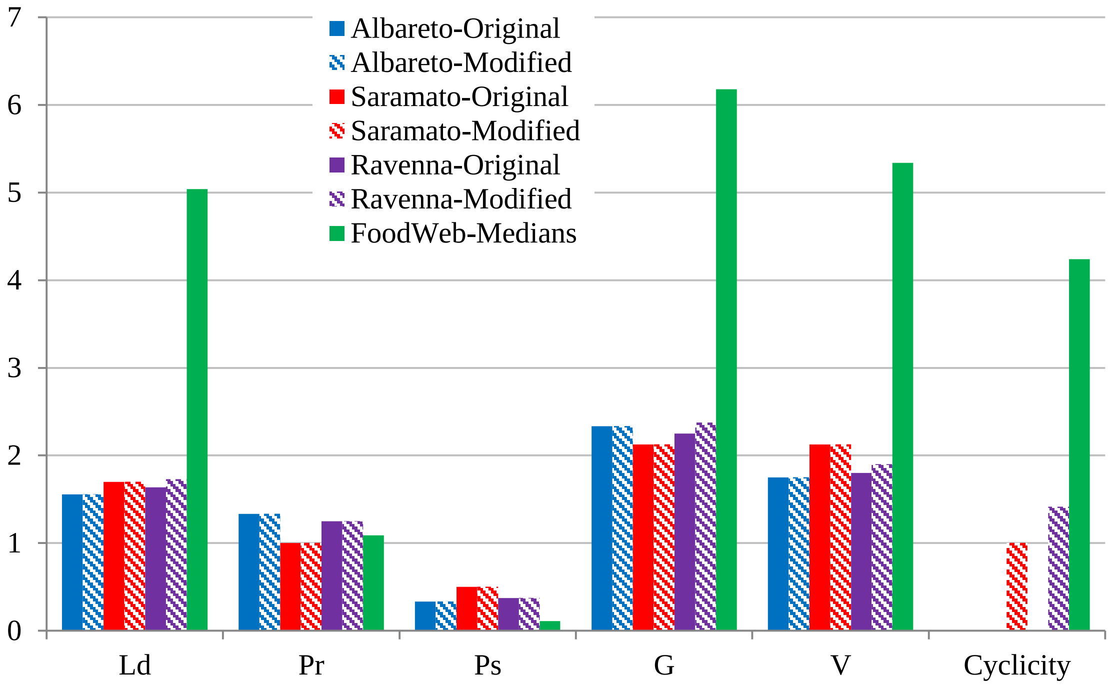


Figure 48: Dimensionless structural metrics for the original and modified water-use networks from Bodini *et al.* (Bodini, Bondavalli et al. 2012) as compared to post-1993 food web medians. *Ld* stands for linkage density, $P_R$ for prey to predator ratio, $P_S$ for specialized predator fraction, *G* for generalization, and *V* for vulnerability.

### 8.5.3 Results for World Zinc Network

No strictly-ecological flow metrics were applied to the zinc market in the original analysis by Graedel *et al*. The world zinc network model is run through a food web flow analysis based on the flow matrix of Figure 49, with results shown in Table 30. The nondimensional metrics $\lambda_{max}$, *MPL*, *AMI*, *ASC*/*DC* and *R* are of interest in a comparison with median food web values.

| | | 0 | **1** | **2** | **3** | **4** | exports 5 | environment 6 |
|---|---|---|---|---|---|---|---|---|
| 0 | import | *0* | *1290* | *6* | *0* | *104* | *0* | *0* |
| **1** | **production, mill, smelter, refinery** | *0* | *0* | *940* | *0* | *0* | *350* | *222* |
| **2** | **fabrication and manufacturing** | *0* | *0* | *0* | *840* | *230* | *0* | *0* |
| **3** | **use** | *0* | *0* | *0* | *0* | *130* | *0* | *0* |
| **4** | **waste management** | *0* | *220* | *120* | *0* | *0* | *0* | *120* |
| 5 | | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| 6 | | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Figure 49: Flow matrix [**T**] for the world zinc market originally investigated by Graedel et al. All flows are measured in grams of zinc. Flow is documented as moving from rows to columns. Rows/columns labeled as 1-4 represent the actors in the world zinc network. Row 0 represents imports from outside the system. Columns 5 and 6 represent exports to outside the system in the form of useable zinc (5) and unusable zinc (6).

Table 32: Flow-based metrics (and three structural characterization metrics) for the world zinc network of Graedel *et al*. (Graedel, van Beers et al. 2005) compared to median food web values for the post 1993 FW dataset.

| | | *Zinc Network* | *Food Web Medians* |
|---|---|---|---|
| Dimensional metrics | **N** | *4* | *51* |
| | **L** | *6* | *249* |
| | ***TSTp*** | $3.88x10^3$ | $1.09x10^4$ |
| | ***ASC*** | $6.72x10^3$ | $1.81x10^4$ |
| | ***DC*** | $1.33x10^4$ | $3.95x10^4$ |
| | ***TSO*** | $6.60x10^3$ | $2.07x10^4$ |
| Non-dimensional metrics | $\lambda_{max}$ | *1.62* | *4.24* |
| | ***CI*** | *0.133* | *0.295* |
| | ***MPL*** | *2.77* | *5.7* |
| | ***AMI*** *(k=1)* | *1.47* | *1.68* |
| | ***ASC/DC*** | *0.505* | *0.372* |
| | ***R*** *(k=1)* | *0.498* | *0.524* |

## 8.6 Discussion: Ecological Flow Metrics

The flow metrics investigated in section 8.3.2 are organized into dimensional metrics and non-dimensional metrics in Table 33 and Table 34. The dimensional metrics (*TSTp*, *ASC*, *DC*, and *TSO*) tend to vary by a factor of 10 at the least between median values for food webs and industrial network values. This variation in scale makes using the dimensional metrics in comparisons difficult . The analyses done in this work compare different types of networks to each other, and so for this reason the non-dimensional metrics will be primarily used.

Table 33: Four dimensional (units of *TSTp*) flow information based metrics (*TSTp*, *ASC*, *DC*, and *TSO*) for the industrial networks described in section 8.3.1 as compared to the median value for the post 1993 food webs.

| | ***TSTp*** | ***ASC*** | ***DC*** | ***TSO*** |
|---|---|---|---|---|
| Albareto - original | $4.60x10^{7}$ | $8.50x10^{7}$ | $9.68x10^{7}$ | $2.02x10^{8}$ |
| Albareto - modified | $4.50x10^{7}$ | $8.35x10^{7}$ | $9.25x10^{7}$ | $1.92x10^{8}$ |
| Saramato - original | $4.83x10^{7}$ | $7.68x10^{7}$ | $1.44x10^{8}$ | $2.59x10^{8}$ |
| Saramato - modified | $4.03x10^{7}$ | $6.35x10^{7}$ | $1.18x10^{8}$ | $2.05x10^{8}$ |
| Ravenna - original | $1.46x10^{9}$ | $2.44x10^{9}$ | $4.72x10^{9}$ | $7.74x10^{9}$ |
| Ravenna - modified | $2.00x10^{9}$ | $2.93x10^{9}$ | $5.95x10^{9}$ | $9.49x10^{9}$ |
| World Zinc Network | $3.88x10^{3}$ | $6.72x10^{3}$ | $1.33x10^{4}$ | $6.60x10^{3}$ |
| Food Web Medians | $1.09x10^{4}$ | $1.81x10^{4}$ | $3.95x10^{4}$ | $2.07x10^{4}$ |

Table 34: Four nondimensional flow information based metrics (*MPL*, *AMI*, *ASC*/*DC*, and *R*) for the industrial networks described in section 8.3.1 as compared to the median value for the post 1993 food webs.

| | ***CI*** | ***MPL*** | ***AMI*** *(k=1)* | ***ASC/DC*** | ***R*** *(k=1)* |
|---|---|---|---|---|---|
| Virtual Water (1896-2001) | | - | - | *0.181* | *0.441* |
| Oil (2007-2011) | | - | - | *0.199* | *0.459* |
| Global Commodity (1962-2010) | | - | - | *0.092* | *0.317* |
| OECD-BRIC Commodity (1988-2010) | | - | - | *0.086* | *0.301* |
| OECD-BRIC FDI (1985-2009) | | - | - | *0.129* | *0.376* |
| Iron and Steel (1962-2011) | | - | - | *0.127* | *0.374* |
| Virtual Water (1896-2001) | | - | - | *0.181* | *0.441* |
| Albareto - ORIG | *0* | *1.18* | *1.14* | *0.478* | *0.509* |
| Albareto - MOD | *0* | *1.17* | *1.11* | *0.483* | *0.507* |
| Saramato - ORIG | *0* | *1.69* | *1.88* | *0.557* | *0.471* |

Table 34 continued: Four nondimensional flow information based metrics (*MPL*, *AMI*, *ASC*/*DC*, and *R*) for the industrial networks described in section 8.3.1 as compared to the median value for the post 1993 food webs.

| | ***CI*** | ***MPL*** | ***AMI*** *(k=1)* | ***ASC/DC*** | ***R*** *(k=1)* |
|---|---|---|---|---|---|
| Saramato - MOD | *0.002* | *1.74* | *1.87* | *0.579* | *0.456* |
| Ravenna - ORIG | *0* | *1.63* | *1.93* | *0.609* | *0.436* |
| Ravenna - MOD | *0.01* | *2.16* | *2.03* | *0.627* | *0.423* |
| World Zinc Network | *0.133* | *2.77* | *1.47* | *0.505* | *0.498* |
| Food Web Medians | *0.295* | *5.7* | *1.68* | *0.372* | *0.524* |

Non-dimensional flow metrics can easily be used in comparisons between different types of networks. Cycling index (*CI*) and mean path length (*MPL*) have already been used to evaluate a carpet recycling network investigated by Reap described in section 8.4.1.5. These two metrics give additional information beyond what is gained from the structural metrics of section 3.3.2. For example the structural metric cyclicity tells if there is cycling present in the systems structure and its relative structural complexity. When used in conjunction with *CI* designers gain knowledge of the level of use of the cyclic pathways. Mean path length, the number of actors "visited" by a material or energy flow. *MPL* describes a level of complexity in the flow or the level of participation of each actor in the path of a particular flow. In a network with low participation a flow may only visit one or two nodes before leaving the system, indicative of a high usage of raw materials and limited or non-existent cycling, resources in such a system are most likely not used to their full potential. The *MPL*, a measure of the number of actors visited by a flow from system inflow to final system outflow, of the zinc and water networks fall well below the median food web value, a range of 1.19-2.77 to a value of 5.7 respectively.

Average mutual information (*AMI*) is representative of how tightly the flow is constrained. The zinc and water networks all have *AMI's* approximately 20% smaller than the median *AMI* for the post 1993 food web dataset. A higher level of constraints is hypothesized to be a reflection of a more developed system (Odum 1969, Ulanowicz 2000, Bodini, Bondavalli et al. 2012).

*AMI* and *MPL* both relate back to the functional prey to predator relationships ($P_S$, $P_R$, $G$, *and* $V$) that determine structure. Constraints on flow path within the system are partially dependent on the directional constraints applied by prey or predator definition. These structural metrics ($P_S$, $P_R$, $G$, *and* $V$) when investigated in section 5.3 showed large gaps between the median structure in the EIPs and in the food webs. As with all structural metrics, $P_S$, $P_R$, $G$, and $V$ place no constraints on the amount of flow that may pass through any link. *AMI* is useful in that it goes one step further by analyzing constraints in terms of flow volumes through the different linkages.

The plot of Figure 50 was modeled after the investigations done by Kharrazi *et al*. and Ulanowicz on system robustness (Ulanowicz 2009, Kharrazi, Rovenskaya et al. 2013). Robustness is the relationship between the organizational constraints on the system and the level of redundancy in the system. Using the post-1993 ecosystems collected in this dissertation from within the *enaR* program (Borrett and Lau 2013) Figure 50 shows that all the food webs reside at the peak of the robustness curve. This result agrees with the assumption that ecological systems have mastered a balance between efficiency and redundancy to maximize their ability to survive system disturbances (Ulanowicz 2009).

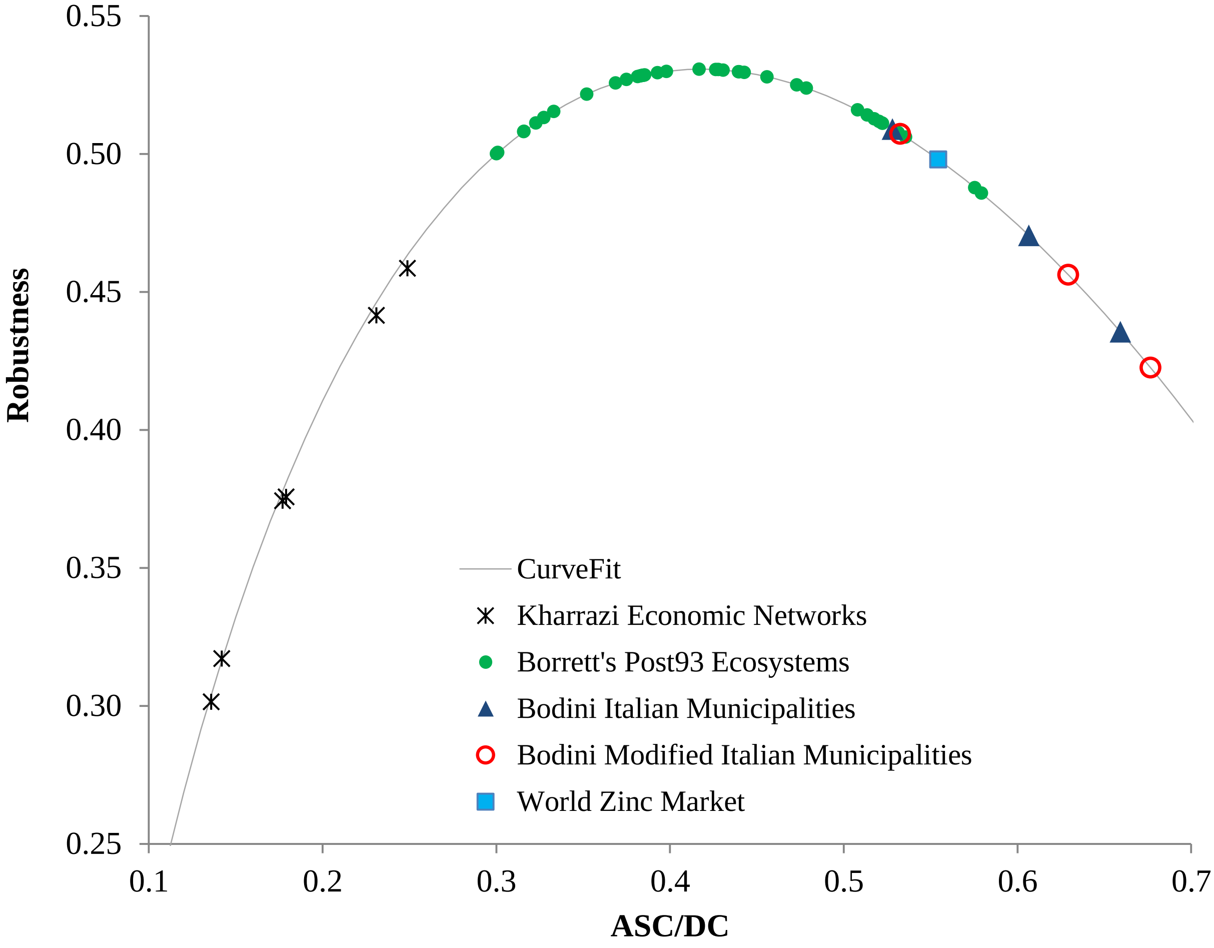


Figure 50: The robustness (*R*) for the networks highlighted in section 8.3.1 are plotted alongside the post 1993 food web dataset in terms of the ratio ascendency (*ASC*) to development capacity (*DC*). Metrics were calculated using *k*=1.

The strength of constraints on a system is also reflected in the ratio of *ASC* to *DC*. Robustness values of all of the networks highlighted in section 8.4.1 are plotted alongside the post 1993 food web data in Figure 50. The apex of the *R* – *ASC*/*DC* curve resides slightly left of center. This is hypothesized by ecologists to be a point of optimality for ecosystems (Ulanowicz 2009) and can be extended to other networks where system disturbances are a similar issue. These networks are characteristic of slightly higher redundancy; usually at the expense of efficiency (maximum efficiency remains the most desirable scenario when there is no potential for adverse disruptions). An industrial network that would benefit from mimicking the robustness levels of food webs would be one where the industrial network has a comparable probability of and aversion to encountering system interference. The Federal Reserve Bank of New York has discussed parallels between the disturbance effects on banks and economic systems and on ecosystems (Kambhu, Weidman et al. 2007, Kambhu, Weidman et al. 2007). Were the measures *R* and *ASC*/*DC* to be used in the bio-inspired design of an at-risk industrial network then it would be advised that additional redundancy be incorporated despite these changes being made at the expense of system efficiency.

System efficiency and redundancy alone do not tell the entire story though; a robust system depends on a balance between these two measures (Ulanowicz 1986, Ulanowicz 2009). Efficiency can reduce cost and consumption but makes the system susceptible to disruptions. Redundancy aids in the systems response in the face of these types of challenges, however it can be expensive to maintain. The ratio *ASC* to *DC* provides a comparison the constraints vs flexibility in the system imposed by efficiency and redundancy.

### 8.6.1 The Economic Resource Networks from Kharrazi *et al*.

The six economic networks from Kharrazi *et al*. all fall to the left of the food webs in Figure 50. This suggests that these economic networks all trade efficiency for a higher level of redundancy. This follows the hypothesis of Bodini and Bondavalli that human systems are characteristic of having large quantities of system imports that tend to be used inefficiently (Bodini and Bondavalli 2002).

### 8.6.2 The Water Usage Networks from Bodini *et al*.

The original water-networks of the three cities investigated by Bodini *et al*. all fall relatively close to the apex of the robustness curve, with a slight bias to the right (the triangles in Figure 50). This suggests that the water usage systems of the Albareto, Saramato, and Ravenna cities balance efficiency and repetition in a manner similar to food webs. The systems could be concluded from these results to efficiently distribute water while maintaining a certain amount of redundancy by way of additional distribution routes available. This is ideal for a water transportation system as it is critical that water may still be dispersed regardless of a failure in the network. The modifications made by Bodini *et al.*, despite being made with the honorable goal of reducing water usage, have shifted each city further from the apex; were these types of modifications to continue the system would be in danger of becoming too restricted and the city's water network susceptible to collapse. The difference between the behavior of the economic networks and the water use networks are most likely due to the fact that an economic network develops over time to maximize profits resulting in efficiency becoming an overriding constraint, while a water distribution network retains the dominating goal of the distribution of water. Had Bodini *et al*. made modifications based on increasing cyclicity and other structural metrics, rather than limiting resource usage this adverse result may have been avoided. This is something that will be investigated in greater depth in the following chapter.

Chapter 4 and sections 6.3, 5.3.1.2, and 3.3.2 conclude cyclicity to be a metric that is very important in the successful imitation of biological networks here. Among the modifications made on the three networks with the goal of reducing resource consumption and thereby fostering sustainability, Table 30 shows that cyclicity was only dramatically increased by changes made for the Ravenna network. The Ravenna water network went from having from no internal cycling to one with complex internal cycling (class B as described in section 6.3.2.2). The changes made to the Albareto network produced no change in cycling (it remained as a class D network with no cycling present) and changes to the Saramato network produced only basic structural cycling where there initially was none (from a class D to class C network).

### 8.6.3 The World Zinc Network from Graedel *et al*.

The structure of a world resource network is not necessarily something that can be directly designed or controlled; it develops as a response to external conditions. Despite this, one can imagine that network robustness is of great interest to all invested parties. Figure 50 shows that the world zinc network of Graedel *et al.* has a robustness lower than what is characteristic of food webs, falling to the right of the peak occupied by the food web networks. This signifies a relatively more efficient network with fewer redundancies. One thought is that system disturbances for this network (and possibly the water networks of Bodini *et al*. as well) are less of an issue, or of a different kind, than what is experienced by food webs. This would create a different optimal robustness point. If the potential for or the consequences of disturbances is similarly significant to food webs, then it may be in the interest to the actors within the world zinc network to increase the redundancy in the network to protect against unforeseen misfortunes.

Important to note is that both Kharrazi *et al*. and Graedel *et al*. looked at economic trade networks but came to polarizing conclusions with regards to the relative levels of efficiency to redundancy in the systems. The network of Graedel *et al*. in terms of the ratio $ASC/DC$ behaves opposite what is seen for the Kharrazi *et al*. networks (Kharrazi, Rovenskaya et al. 2013), which shows a high level of redundancy at the expense of efficiency. Both network groups still show lower robustness values though. Less concerning is the opposite behavior of the water distribution networks of Bodini *et al*. as the distribution of water has different requirements imposed due to being a support network for human life. The differences may be due to unintentional variance, or variance associated with constraints on the systems. Kharrazi *et al*. do not provide the numerical information used in their paper to calculate $R$ and $ASC/DC$ and so it is difficult to know what if any effect the researchers had in producing this result.

Flow based metrics (robustness in particular it will continue to be seen) can add much in the way of describing and understanding a system. The robustness of the networks described in this chapter up to this point is a product of the collective properties of the actors making up the system. None of these networks had a designer making decisions to control the resultant robustness. These networks are all “complex adaptive systems” where the system does not adapt with any coordination but rather it is the components that change in their own best interest in response to external conditions (Kambhu, Weidman et al. 2007). The thermodynamic power cycles in chapter 4 are an interesting set of networks to study since they are designed with the specific purpose of maximizing efficiency, unlike these adaptive systems. The power cycles were found in chapter 4 to have higher values of cyclicity as changes in structure were implemented to increase their thermodynamic efficiency. With the findings of section 8.4, efficiency-motivated design decisions and the resultant cyclicity and can be related to effects on the system robustness.

## 8.7 A Flow Analysis of Previously Investigated Thermodynamic Power Cycles

Chapter 4 used well understood thermodynamic power cycles to investigate the ecological metric cyclicity. Thermal efficiency measures the success of the system in producing a net work-output in terms of input heat. Comparing this thermodynamic measure to cyclicity, chapter 4 showed that thermodynamic systems with higher thermal efficiency values were also characteristic of higher cyclicity values. The higher cyclicity values in the power systems represented the superior use of the available energy in the system: this is analogous to the representation of higher cyclicity values in an ecosystem. A flow-based analysis can also be done for the thermodynamic power cycles of chapter 4.

### 8.7.1 Methods: Setting up a Flow Analysis of Thermodynamic Power Cycles

The energy in the material flowing through the basic Brayton cycle of Figure 51 with system properties outlined in

Table 35 can be followed using the enthalpies entering and exiting each system component (node). These values were collected in chapter 4 using equations 18-20. The work and heat into and out of the system were then calculated from this information. The resultant values of energy flowing through, into, and out of the system, measured in [kJ/kg], complete the flow matrix [**T**] as outlined in Figure 45. Inputs to the system from across the system boundaries occur at node one in the form of the initially input material flowing through the system and at node two in the form of input heat to the combustor. Outputs from the system occur at node three and include energy dumped to the environment in the form of left over material flow, heat transfer due to a temperature difference between the material flow and the environment, and work produced by the system. The values of the entries in the flow matrix [**T**] are calculated from the information collected in Table 36.

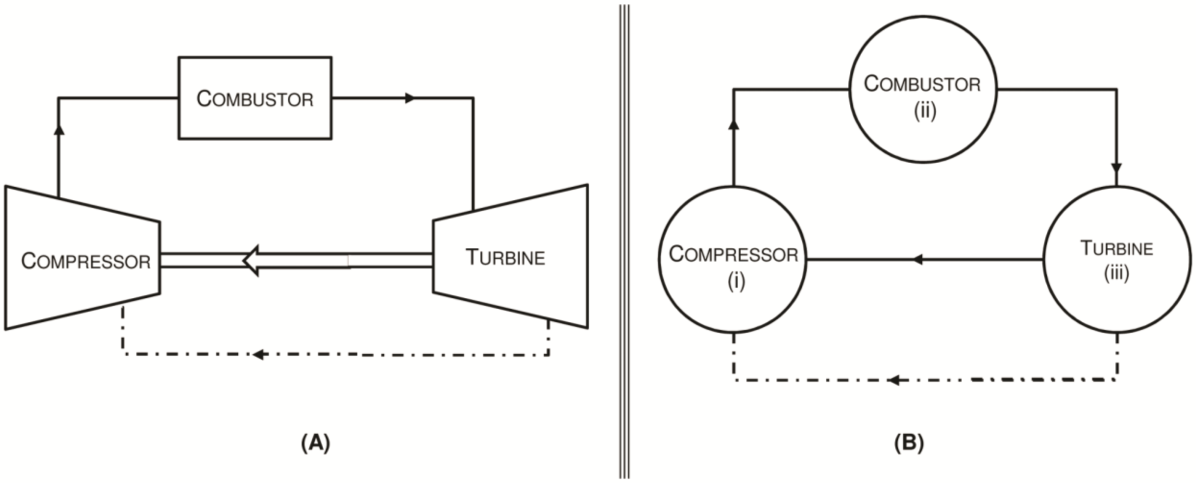


Figure 51: Basic Brayton cycle idealized equipment diagram for a power cycle (a), energy flow diagram (b).

Table 35: Specified state point data for all ideal Rankine and Brayton cycle analyses (reprinted Table 4).

| **Rankine Cycles - water** | **Brayton Cycles - air** |
|---|---|
| $T_{min}$= 318.9 K | $T_{min}$ = 288.2 K |
| $T_{max}$ = 873.2 K | $T_{max}$ = 1273 K |
| $P_{pump1,input}$ = 10 kPa | $P_{compresser,input}$ = 100 kPa |
| $P_{boiler,input}$ = 15000 kPa | $r_p$=10 (pressure ratio) |

Table 36: State point information for the basic Brayton cycling of Figure 51 using the temperature and pressure information from

Table 35. This information was used to fill in the flow matrix [**T**].

| | T [K] | *h* [kJ/kg] |
|---|---|---|
| into (*i*) | *318.9* | *288.6* |
| out of (*i*) into (*ii*) | *540* | *557.7* |
| out of (*ii*) into (*iii*) | *876.2* | *1364* |
| out of (*iii*) into environment | *770* | *723.8* |

| | [kJ/kg] |
|---|---|
| $W_{in}$ into (*i*) | *269.1* |
| $Q_{in}$ into (*ii*) | *806.4* |
| $W_{out}$ out of (*iii*) | *640.3* |
| $Q_{out}$ out of (*iii*) | *435.2* |

$$[\mathbf{T}] = \begin{array}{c|cccccc|c} & 0 & 1 & 2 & 3 & 4 & 5 & values \\ \hline 0 & 0 & h_1 & Q_{in} & 0 & 0 & 0 & t_{01} = 289 \\ 1 & 0 & 0 & h_2 & 0 & 0 & 0 & t_{02} = 807 \\ 2 & 0 & 0 & 0 & h_3 & 0 & 0 & t_{12} = 558 \\ 3 & 0 & W_{in} & 0 & 0 & \begin{matrix} W_{out} - W_{in} \\ +Q_{out} + h_4 \end{matrix} & 0 & t_{23} = 1364 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & t_{31} = 269 \\ 5 & 0 & 0 & 0 & 0 & 0 & 0 & t_{34} = 1530 \end{array}$$

Figure 52: Flow matrix [**T**] for the basic Brayton cycling. Row 0 is inputs to the system, column 4 contains outputs from the system, and column 5 contains dissipations to the outside environment.

### 8.7.2 Results: Flow Analysis of Thermodynamic Power Cycles

Nine flow based ecological metrics are calculated from equations 24-32 for the basic Brayton cycle. The values for the basic Brayton cycle and basic Rankine cycle are listed alongside median values for the post 1993 set of food webs in

Table 37. Cyclicity and thermal efficiencies are also listed here to aid in comparison with the previous analysis of chapter 4. A constant multiplier (*k*) of 1 was used in the calculation of *AMI*, while recognizing that the previous analysis of Kharrazi *et al*. described in section 8.4.1.2 used a *k* of 0.7 (Kharrazi, Rovenskaya et al. 2013). This multiplier is usually set to a value of one in ecological analyses, for example a multiplier of one is used in the *enaR* package that populated the values for the dataset of food webs from Borrett (confirmed in personal communications).

Table 37: Resultant flow metrics for the basic Brayton cycle of Figure 52 and the basic Rankine cycle compared to their structurally more complex counterparts and medians for the post 1993 food web dataset as calculated by enaR (Borrett and Lau 2013). The constant multiplier *k* for the metric *AMI* was set equal to one in order to match the ecological analyses of Borrett and Lau.

| | | **FW Medians** | **Basic Brayton** | **Brayton with 3 reheaters & intercoolers** | **Basic Rankine** | **Rankine with 8 open feedwater heaters** |
|---|---|---|---|---|---|---|
| Dimensional (units of *TSTp*) | ***TSTp* (flow units)** | $1.09x10^4$ | $4.82x10^3$ | $1.68x10^4$ | $1.31x10^4$ | $2.03x10^4$ |
| | ***ASC*** | $1.81x10^4$ | $7.22x10^3$ | $5.51Ex10^4$ | $2.22x10^4$ | $6.63x10^4$ |
| | ***DC*** | $3.95x10^4$ | $1.11x10^4$ | $7.49x10^4$ | $3.15x10^4$ | $8.53x10^4$ |
| | ***TSO*** | $2.07x10^4$ | $3.89x10^3$ | $1.99x10^4$ | $9.27x10^4$ | $1.90x10^4$ |
| Non-dimensional | ***CI*** | *0.295* | *0.197* | *0.466* | *0* | *0.186* |
| | ***MPL*** | *5.7* | *3.00* | *14.6* | *2.65* | *6.58* |
| | ***AMI* (*k* = 1)** | *1.68* | *1.50* | *3.27* | *1.70* | *3.26* |
| | ***ASC/DC*** | *0.372* | *0.650* | *0.735* | *0.706* | *0.78* |
| | ***R* (*k* = 1)** | *0.524* | *0.404* | *0.327* | *0.355* | *0.283* |
| | $\lambda_{max}$ | *4.24* | *1.00* | *1.47* | *0* | *1.27* |
| | **thermal efficiency - $\eta_I$** | - | *0.482* | *0.733* | *0.430* | *0.483* |

## 8.8 Discussion: Ecological Flow Patterns in Thermodynamic Power Cycles

Thermodynamic efficiency was shown in section 4.3 to positively correlate with the food web metric cyclicity.

Table 37 compares side by side the increases in thermal efficiency between the most basic power cycles and their more structurally complex counterparts (a Brayton cycle with 3 reheaters and intercoolers and a Rankine cycle with 8 open feedwater heaters). The flow metric values for all fourteen power cycles can be found in Table A48 and Table A49 of appendix A. The increase in thermal efficiency, from *0.430* to *0.483,* between the basic Rankine cycle and the cycle after the incorporation of 8 feedwater heaters, shows an increase in the average mutual information (*AMI*). This is as expected since the addition of the feedwater heaters results in a more complex flow path that the working fluid must travel, or an increase in the constraints on the flow paths within the system – the conceptual meaning of *AMI*.

Bodini and Bondavalli hypothesized that human systems are characteristic of high development capacity (*DC*) values as they tend to process large amounts of external inputs (natural resources) but low system ascendency (*ASC*) due to the inefficient use of said resources (Bodini and Bondavalli 2002). Increases in *ASC* and total system overhead (*TSO*) are believed to be representative of a more highly evolved system (Kharrazi, Rovenskaya et al. 2013). It should be recognized that human systems are often unintentionally designed, in these cases the configuration is the result of external requirements placed on the system (e.g. profit maximization and distribution). This type of development, as a response to externally imposed requirements, is characteristic of ecosystems.

Increases in development capacity for both the Rankine and Brayton cycles are seen in

Table 37. The Rankine and Brayton cycle have increases in *DC* of the same order of magnitude between the most basic to most efficient scenario: *53800* and *63800* respectively. The increases represent a higher potential for additional evolution in the complex form of both cycles.

The system ascendency, the degree to which the system efficiently distributes flows between components, shows an increase between the system configurations. The Rankine and Brayton cycle have a similar increase in *ASC* between the most basic to most efficient scenario: *44100* and *47880* respectively. The modifications made to the basic cycles were made with the goal of increasing how efficiently the system converts input heat into a usable work output (measured by thermal efficiency calculated from equation 17). Unlike the response-triggered development of ecosystems and industrial systems, here we can see the effect of design decisions. Decisions made to increase thermal efficiency in these networks also result in an increase in flow distribution efficiency.

$$DC = TSO + ASC \tag{29}$$

The large increases in *ASC* and *DC* of the thermodynamic power cycles may be explained by the relationship of equation 29 (reprinted here for the reader's convenience), an increase in *TSO*: *9730* and *16010* for the Rankine and Brayton cycles respectively. This relationship says that although the thermodynamic systems become more thermally efficient with the selected modifications, there is an increase in the redundancy (*TSO*) in the system as well that keeps *ASC* from reaching *DC*, it's upper bound. This observation can be summarized as: the addition of any amount of complexity to the system structure prevents the system from achieving 100% efficiency. This is in accordance with the second law of thermodynamics, that no system can be 100% efficient, i.e. the work output from the system can never equal the heat input to run the system. This law is illustrated by Figure 19 in section 4.3.

System efficiency vs redundancy can also be understood using robustness (*R*) from equation 34. This relationship is described visually in Figure 53, showing robustness as a function of the degree of order (*ASC*/*DC*) in the system. The post-1993 food webs are shown in green and all reside at the peak of the curve in Figure 53. This agrees with the assumption that these ecological systems have mastered a balance between efficiency and redundancy, maximizing their ability to survive system disturbances. The thermodynamic power cycles investigated here all fall from the apex and to the right. This behavior mimics the effect of efficiency increases in the water networks of Bodini *et al*. seen in Figure 50. The difference between the economic networks in Figure 50 and the thermodynamic cycles in Figure 53 is in the threat of system disturbances. System disturbances are not an issue for ideal thermodynamic power cycles, therefore adding redundancy to increase robustness would be a poorly made design decision. Issues that require some amount of network robustness, such as economic instability, species extinction, and climate disturbances, do not concern the operation of thermodynamic power cycles.

The data in Figure 53 tells the story that thermodynamic cycles very efficiently make use of minimal system imports. The most complex power cycles investigated are the Rankine cycle with 8 feedwater heaters and the Brayton cycle with 3 reheaters and 3 intercoolers. These systems both fall farthest to the right of the apex in Figure 53 with very low robustness values. The most basic versions of each power cycle reside closer to the apex in contrast. This follows the ecological explanation that systems gain efficiency at the sake of redundancy.

The most basic networks however are not the most robust however. There is one Brayton cycle and two Rankine cycles that are more robust than the most basic versions of these systems, despite having a higher efficiency. This cause and effect is reflected in the design decisions made here for the Rankine and Brayton cycles under the goal of maximizing thermal efficiency. The Brayton cycle with the highest calculated robustness is the one with the simplest modification made – only regeneration is added. This modification results in an increase in thermal efficiency (from 0.482 to 0.563) in addition to a slight increase in robustness (0.404 to 0.498), not what is expected from efficiency increases. This can only mean that the development capacity increased more than the system ascendency, or the modifications made that increased the efficiency also added additional repetition to the system. This is confirmed by looking at the structural representation of the Brayton cycle with regeneration. The same trend is seen for the Rankine cycles. The first three modifications made to the Rankine cycle (the incorporation of 1, 2, and then 3 open feedwater heaters) result in increases or no change in robustness values. The highest robustness value comes from the 6th modification made – Rankine cycle with 6 open feedwater heaters. All the modifications made to the Rankine cycle increase the efficiency, but at different points the modifications also add repetition. This shows that it is in fact possible to make design decisions that both increase efficiency and repetition, thereby increasing the systems robustness. The increase of efficiency and repetition are not mutually exclusive results, although in general efficiency increases do reduce system robustness.

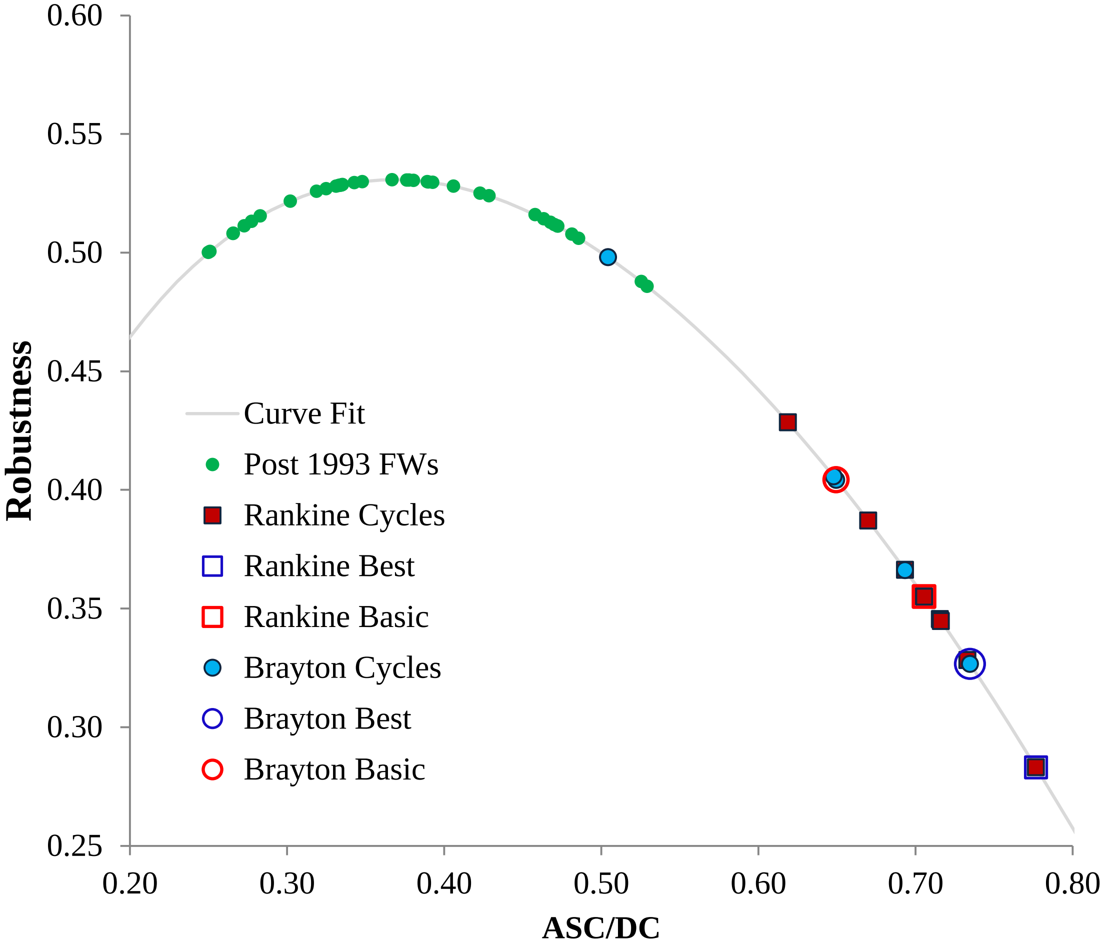


Figure 53: Ascendency to development capacity ratio vs robustness for the Brayton and Rankine cycles investigated, as compared to the post 1993 ecosystems from Borrett and Lau (Borrett and Lau 2013). The scaling constant *k* has been set to one here in accordance with the methods of Borrett and Lau.

The relationship between thermal efficiency, robustness, and *ASC*/*DC* is further clarified by the plots in Figure 54. The plot in (Figure 54 – left) shows a decline in system robustness after an initial increase as thermal efficiency increases. Due to the results of Figure 20 in section 4.3 that showed a positive linear relationship between thermal efficiency and cyclicity, large increases in the metric cyclicity can be extrapolated to also cause decreases in system robustness.

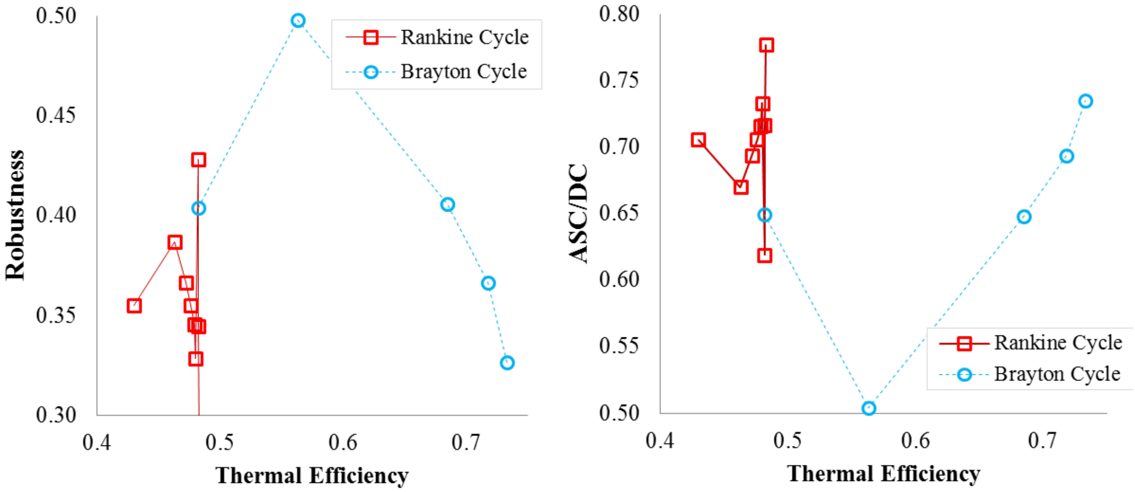


Figure 54: A comparison of the thermodynamic power cycles thermal efficiencies against the ecological metric robustness (*R*) (figure on the left) and the ratio *ASC*/*DC* (figure on the right).

The characteristic behavior between the Rankine and Brayton cycles is that changes in the structure of the Brayton cycle result in much larger increases in thermal efficiency than changes in the Rankine cycle. This behavioral difference was explained in chapter 4 in ecological terms: the Brayton cycle has more system components that act as detritivores – sending low quality energy that would otherwise be at the end of its path back to the actors at the start of the paths (the high quality energy users – or primary producers in ecological terms). This is reflected by the results in

Table 37 with a significantly higher *MPL* for the complex Brayton cycle as compared to the complex Rankine cycle, a value of 14.6 as compared to 6.59 when both cycles began with a *MPL* around 3.

This rate difference is reflected in both plots of Figure 54. Figure 54 – left shows that, after the initial increase in robustness of the first three configurations, small increases in thermal efficiency in the Rankine cycle cause a sharp decrease in robustness, while the negative effect seen in the Brayton cycle is more gradual after the initial increase despite larger thermal efficiency gains. This can be attributed to thermal efficiency's relationship with *ASC*/*DC* in Figure 54 – right. The structural changes in each of the power cycles, although resulting in different thermal efficiency gains, show similar final constraint levels placed on the system. This can be attributed to a larger increase in the development capacity due to structural changes in the Brayton cycles ($\Delta DC = +63{,}800$ for the Brayton cycles and $\Delta DC = +53{,}800$ for the Rankine cycles). Increases in *ASC* for the two cycles were more similar ($\Delta ASC = +47{,}800$ for the Brayton cycles and $\Delta ASC = +44{,}100$ for the Rankine cycles).

### 8.9 Conclusions

The incorporation of non-dimensional flow based metrics used to describe ecosystems into the design portfolio for use with industrial networks has many potential benefits. The flow-information based metrics mean path length and robustness (*MPL* and *R*) show particular promise in aiding network designers with the creation of biologically similar industrial resource networks. These flow-based design metrics are qualitatively investigated using the thermodynamic power cycles and first law efficiency initially presented in chapter 4.

Existing literature (Reap 2009) has suggested at the added value the inclusion of *CI* and *MPL* have to a structural analysis. This finding is confirmed here, quantitatively confirming that a higher *MPL* informs designers to the presence of active detritus-type actors in the system. These detritus-type actors have in earlier chapters also been connected to higher cyclicity values.

The economic and distribution networks investigated here were found to poorly mimic median food web values, and this includes values *MPL*. These ranged from approximately 1 to 2 while the median value for food webs is 5.7. This metric can be increased in industrial networks by designing additional recycling actors into the system, this in turn will increase the number of actors an imported flow “visits” before being exported.

A thermodynamic investigation shows that the increase of efficiency and repetition are not mutually exclusive results, although in general efficiency increases do reduce system robustness. A hypothesized optimal point for food webs is the apex to the robustness curve, after this point gains in efficiency start to be made at the expense of robustness in addition to redundancy. Robustness for system where external stressors are a potential threat is an important component of ensuring the system is sustainable. If system disturbances are an issue for the network in question then a bio-inspired solution would be to incorporate redundancy at the expense of efficiency till the point of maximum robustness is reached (around an *R* value of approximately 0.53). This maximum robustness is where ecological food webs are shown to cluster. An economic network was shown to be characteristic of a higher level of redundancy (an *ASC*/*DC* value below the hypothesized optimal point) while two types of distribution networks investigated were shown to be characteristic of higher levels of efficiency (an *ASC*/*DC* value above optimal). Thermodynamic cycles generally do not deal with system perturbations and therefore robustness losses due to efficiency driven modifications are not an issue.

Robustness and *MPL*, along with the other flow-based metrics introduced are further studied in the chapter 9 following through their application to the carpet recycling network introduced in section 8.4.1.5.

# CHAPTER 9

# FLOW ANALOGY: APPLICATION TO A CARPET RECYCLING MODEL

## 9.1 Research Questions to be Addressed

With the introduction of ecological flow-based metrics for use in eco-industrial parks the field of bio-inspired design may be pushed forward. Combining the structural-ecological analysis of eco-industrial parks with flow-based analyses provides additional information that can help advise the formation of sustainable design guidelines. With the translation of the principles, definitions and metrics from chapter 8, an exploration of the potential of a flow-based ecological analysis can be investigated, something that has yet to be done in the field. This chapter presents an expansive analysis combining flow metrics with structural metrics using a previously published carpet recycling network. The conclusions drawn from the carpet recycling network address the research goal of investigating the ecological flow-based analyses of food webs and applying it to industrial networks. The results also help to meet the overarching goal of this dissertation and the field of industrial ecology: showing that bio-inspired design guidance will lead to sustainable industrial resource networks. Through the exploration of flow analyses coupled with the already investigated structural analyses this chapter hopes to help answer the following two questions: What is the resultant value to industry of an ecological analysis based on flow information in? What if any additional insight is provided from a flow-based ecological analysis that is not available from a purely structural analysis? This chapter seeks to contribute to a better understanding of flow based metrics in food webs and their use in industrial networks. The work here also contributes to the larger research goal of creating design guidance for the construction and development of successful EIPs.

## 9.2 Background: A Carpet Recycling Model

An existing optimization model done by Reap on a carpet recycling network in Atlanta, GA, USA compares a traditional profit-based flow optimization to a bio-inspired food web metrics based flow optimization (Reap 2009). The model, shown in Figure 55, consists of one carpet manufacturing facility with two external inputs of new PVC and Nylon 6,6. Populating the rest of the network are 9 landfills, 15 reuse or recycling facilities, and 13 counties that consume and or store carpet. The network results in 38 actors (i.e. 85 possible flows) and 26 design variables that represent potential flows of carpet for recycling and reuse. Each of the 13 counties has two design variables, one for carpe sent to reuse and one for carpet sent to recycling. The recycling and reuse facilities interact with both the individual counties and the original carpet manufacturer. The overall cost of the network is made up of material costs, labor costs, and energy costs.

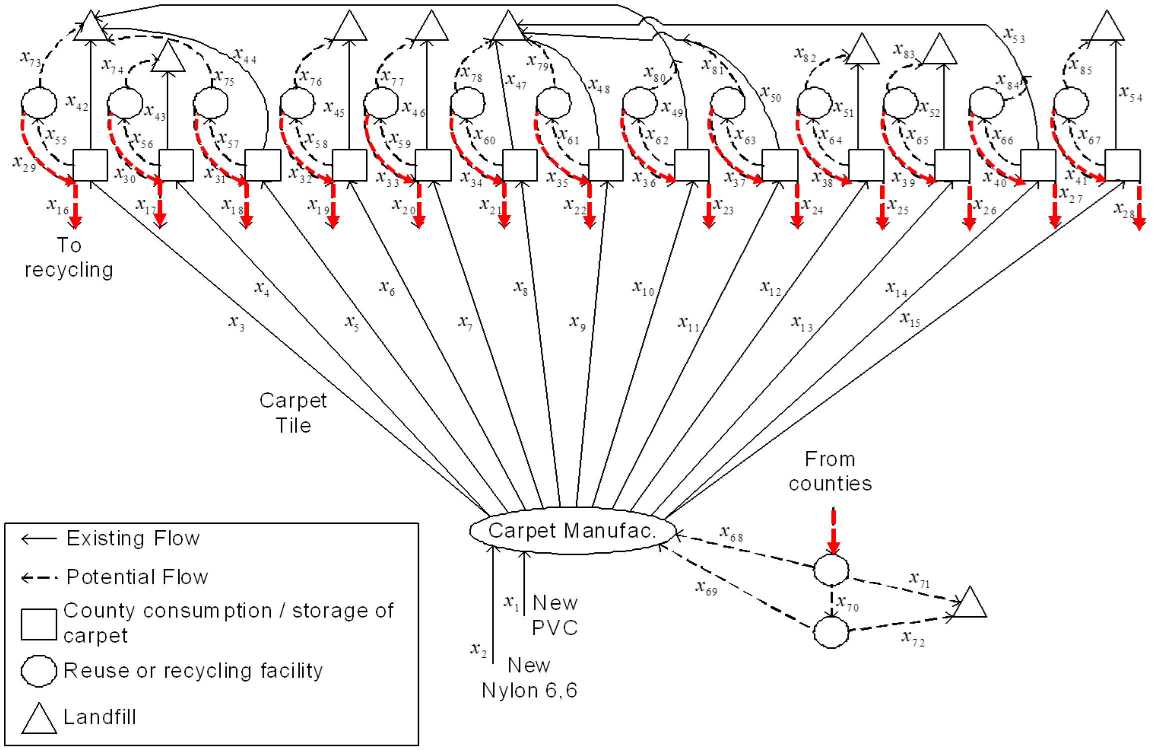


Figure 55: Carpet recycling network model showing existing and potential carpet tile and carpet tile material flows. The vectors highlighted in red represent the linkages in the design vector. *Figure modified and reprinted with permission from* (Reap).

The original analysis by Reap solved for a design vector made up of flows for the 26 design variables representing carpet sent to recycling and reuse centers: linkages $x_{16}$ – $x_{41}$highlihgted in red in Figure 55. The model allows the user to vary the amount of materials transported as represented by the design variables, from a value of zero to a maximum established by a set of specified problem constraints. The constraints include capacity limits for reuse and recycling. A traditional objective function ($Z_{trad}$) and a bio-objective function ($Z_{bio}$) were then calculated using each design vector.

The bio-inspired objective function used 9 equally weighted food web metrics to select the carpet flows: 7 structural metrics and 2 flow-based metrics listed in Table 38. The structural metrics used were linkage density, prey to predator ratio, fraction specialized predator, generalization, vulnerability, connectance (calculated with cannibalism), and cyclicity. The flow-based metrics used were mean path length and cycling index. The bio-inspired objective function value was calculated by summing equally weighted deviations between the calculated food web metric and a set goal value, or the target value, of each metric. The deviations were calculated by equation 1 and 2 depending on if the metric calculated was greater than or less than the target value, respectively. The goal values for the biological objective function are shown in Table 38. The target values in this table for the first 6 structural metrics are medians taken from ecosystems collected by Briand (Briand 1983), the median for the metric cyclicity was taken from Fath (Fath and Halnes 2007), and the medians for the flow metrics CI and MPL were taken from Finn and Bailey (Finn 1976, Bailey 2000). The weighting factor used by Reap was (1/9), thereby weighting each metric deviation equally. The bio-inspired model results in a non-linear, mixed integer solution space and was unable to be solved using traditional optimization algorithms. A stochastic search was used instead and found to result in a desirable design solution, however not a true optimum.

$$d_{min} = 1 - \frac{metric}{metric, goal} \tag{33}$$

$$d_{max} = 1 - \frac{metric, goal}{metric} \tag{34}$$

Table 38: The goal values used for the bio-inspired objective function from Reap's carpet recycling model (Reap 2009) taken from ecosystems collected and/or analyzed in the literature (Finn 1976, Briand 1983, Bailey 2000, Fath and Halnes 2007).

| *Bio-inspired Objective Function Goals* | **Reap 2009 goal values used** |
|---|---|
| **Link density ($L_d$)** | *0.24*N* |
| **Prey to Predator Ratio ($P_R$)** | *0.94* |
| **Specialized Predator Fraction ($P_S$)** | *0.403* |
| **Generalization ($G$)** | *2.23* |
| **Vulnerability ($V$)** | *2.64* |
| **Connectance (calculated with cannibalism) ($c$)** | *0.12* |
| **Cyclicity ($\lambda_{max}$)** | *7.14* |
| **Cycling Index ($CI$)** | *0.295* |
| **Mean Path Length ($MPL$)** | *5.7* |

The traditional objective function selected for flows such that the total network cost and emissions were minimized. Twelve emissions were modeled: carbon dioxide, methane, nitrous oxide, sulfur dioxide, nitrogen oxides, lead, carbon monoxide, volatiles organic carbons, mercury, hydro-carbons, particulate matter, and lead ($CO_2$, $CH_4$, $N_2O$, $SO_2$, NOx, Pb, CO, VOCs, Hg, HC, PM, and SOx). Emissions originated from the manufacture of virgin PVC, nylon 6,6, and a deep cleaning solution, the generation of electricity specific to Georgia, natural gas, and trucks for transportation relating to their speed, load capacity and fuel efficiency. This required the calculation of distances traveled between actors, knowledge of the types of vehicles used and their emissions based on load weight, and detailed information about manufacturing and demanufacturing processes. Total network cost included the cost of new PVC and nylon 6,6, the cost of natural gas and diesel, electricity, landfill costs, and the cost of labor at all stages. The full table of detailed equations used by Reap may be found in (Reap 2009). The traditional objective function value was calculated by summing equally weighted deviations between the calculated emissions and cost, and a set goal value, or the target value, for each. The deviations were calculated by equation 1. The target values for each of the twelve emissions and total cost are shown in Table 39. The target values for the emissions were taken from the best possible scenario for the model (emissions only due to transportation across the existing flow linkages in Figure 55) multiplied by a goal scaling value of 0.8 (Reap 2009). The total cost goal value is a guess known to be below the solution multiplied by the goal scaling value of 0.8 again (Reap 2009). The weighting factor used was (1/13), thereby weighting each emission and cost deviation equally. The traditional solution was minimized with a constrained linear optimization using MATLAB's "fmincon" solver.

Table 39: The goal values used for the traditional objective function from Reap's carpet recycling network model (Reap 2009). Values are taken from the best possible scenario for the model multiplied by a goal scaling value of 0.8. Emissions are measured in grams and cost in US dollars.

| *Traditional Objective Function Goals* | **Reap 2009 goal values used** |
|---|---|
| **$CO_2$** | $6.67 \times 10^{9}$ |
| **$CH_4$** | $3.17 \times 10^{7}$ |
| **$N_2O$** | $3.02 \times 10^{5}$ |
| **$SO_2$** | $3.06 \times 10^{7}$ |
| **NOx** | $2.25 \times 10^{7}$ |
| **Pb** | $1.43 \times 10^{3}$ |
| **CO** | $1.75 \times 10^{7}$ |
| **VOCs** | $3.50 \times 10^{4}$ |
| **Hg** | *52* |
| **HC** | $4.35 \times 10^{6}$ |
| **PM** | $3.02 \times 10^{6}$ |
| **SOx** | $1.50 \times 10^{7}$ |
| **Total Cost** | $5.90 \times 10^{6}$ |

The original analysis created 100,000 randomly chosen design vectors, or designs, that met system constraints, and calculated both the bio-inspired and traditional objective function for each. The results of the original analysis showed that the carpet recycling network when designed to mimic food webs positively correlated with standard cost- and emissions-minimizing designs, resulting in an $R^2$ value of 0.96 (Reap 2009). Figure 56 confirms that the original result found by Reap can be replicated, generating 100,000 randomly chosen designs and plotting the calculated traditional and bio-inspired objective function values for each.

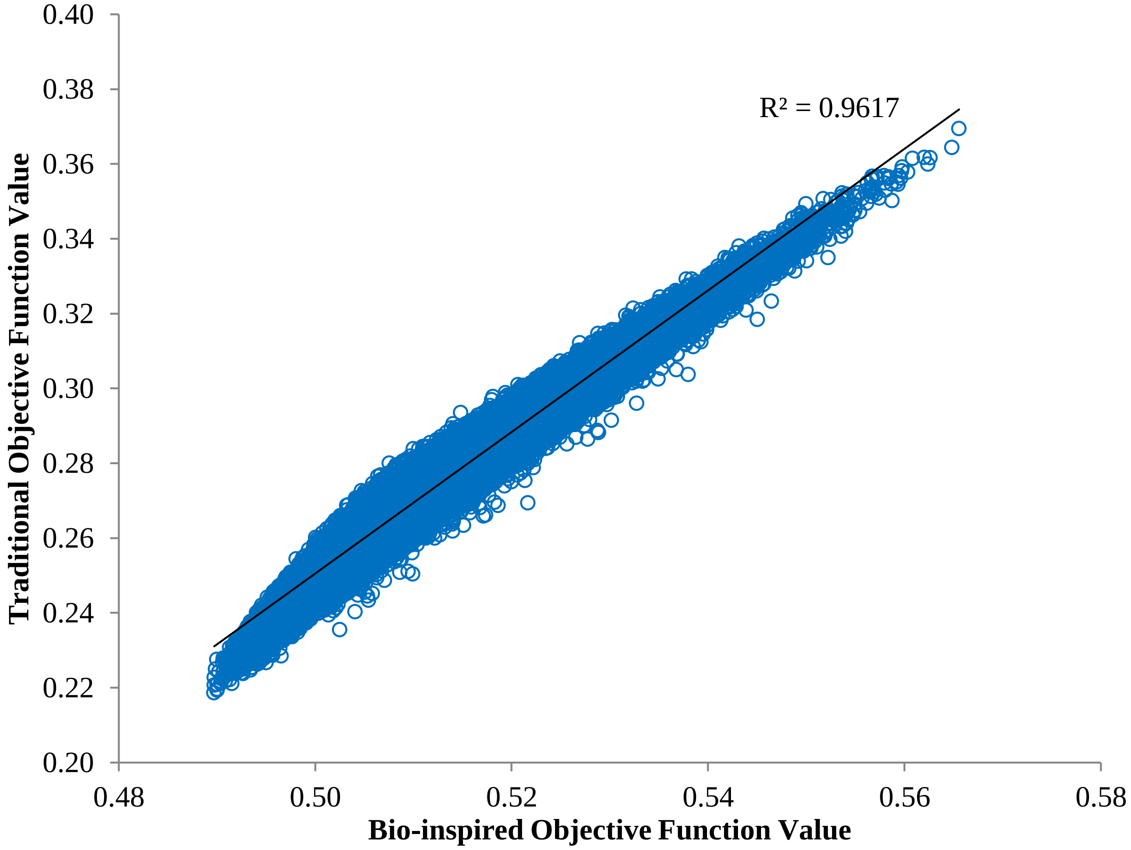


Figure 56: Traditional vs. Bio-Inspired Objective Function Values for 100,000 Randomly Generated Carpet Tile Recycling Network Designs.

## 9.3 Methods

### 9.3.1 Modifications Made to Original Methods: Target Food Web Values

The first modification made to the original analysis described above in section 9.2 was to the goal values used for the food web metrics. The original target values for the food web metrics are listed in Table 38. These values are updated using median values from the post 1993 food web dataset collected in chapter 5, following the design advice of sections 5.2.2 and 5.4. These updated values are listed in Table 40.

Table 40: The median target food web values from the original analysis as compared to the target values used here: median values from the post 1993 food web dataset.

| *Food Web Metrics Used as Goal Values* | **Reap 2009 FW median goal values used** | **New median goal values for FWs collected 1993+** |
|---|---|---|
| **Link density ($L_d$)** | *0.24*N* | *5.04* |
| **Prey to Predator Ratio ($P_R$)** | *0.94* | *1.09* |
| **Specialized Predator Fraction ($P_S$)** | *0.403* | *0.10* |
| **Generalization (*G*)** | *2.23* | *6.18* |
| **Vulnerability (*V*)** | *2.64* | *5.34* |
| **Cyclicity ($\lambda_{max}$)** | *7.14* | *4.24* |
| **Cycling Index (*CI*)** | *0.295* | *not changed* |
| **Mean Path Length (*MPL*)** | *5.7* | *not changed* |

Cycling index (*CI*) and mean path length (*MPL*) were not updated from the values used by Reap as not enough flow data was available at the time the analyses were run to update them. The metric connectance was dropped from the bio-inspired objective function based on conclusion that it depends very strongly on the size of the network (sections 3.4 and 5.4.7). The post 1993 food web dataset does not contain enough food webs of a size similar to the carpet recycling network (*N*=38) so an acceptable median value is not available.

Thus 8 metrics are left (listed in Table 40) for use in calculated the bio-inspired objective function: 6 structure-based metrics and 2 flow-based metrics. The group ‘6 structural metrics’ refer to link density, prey to predator ratio, specialized predator fraction, generalization, vulnerability, and cyclicity. The group ‘all eight metrics’ refers to the six structural metrics plus cycling index and mean path length.

Table 40 shows that the target value for link density as used in the original analysis was an equation dependent on network size ($N$). The new target values for the food web metrics based on the post 1993 food web dataset showed the possibility of using either an equation or a median value as a replacement. An equation replacement of the original $L_d$ target value was tested and found to be a poor representation of the behavior of linkage density with changes in network size. As a result a numerical median was used for the analyses here, as listed in Table 40.

The original analysis by Reap resulted in the very high correlation between the network when designed to match target values for the food web metrics – or minimize the bio-inspired objective function value ($Z_{bio}$), and the minimization of cost and emissions for the network or the traditional objective function value ($Z_{trad}$). Thus minimizing $Z_{bio}$ by meeting target values for the selected food web metrics also minimized $Z_{trad}$ as defined by the cost and emissions of the network. The bio-inspired objective function in this case was calculated by weighting all of the food web metrics equally, thus the deviation of any one of the metrics from the target value contributed equally to the value of $Z_{bio}$. There is very likely a dominance of one of more of the food web metrics that is controlling the resultant design vector and thereby the correlation between $Z_{bio}$ and $Z_{trad}$. With the target values for the food web metrics reset based on the new food web dataset used in this dissertation, variations on the original analysis can be run to test for the possibility of this dominance and other behaviors.

### 9.3.2 Modifications Made to Original Methods: Design Generation

The numerous scenarios run using the original code from Reap very quickly revealed that without the two flow metrics cycling index (*CI*) and mean path length (*MPL*), the bio-objective function ($Z_{bio}$) breaks down, or in other words when only structural metrics were used to select the design, the objective function for the bio-model does not change, as seen by the vertical line of red square-signifiers in Figure 57 ("w/o random multiplier"). The design is meant to be generated randomly, but as the code is originally written there is a bias towards assigning a nonzero value to the flows in the design vector ($x_{16} – x_{41}$). Due to this bias, when only structural metrics are used to calculate the bio-inspired objective function, there is no change in its value with each new design as all links are turned 'on' regardless.

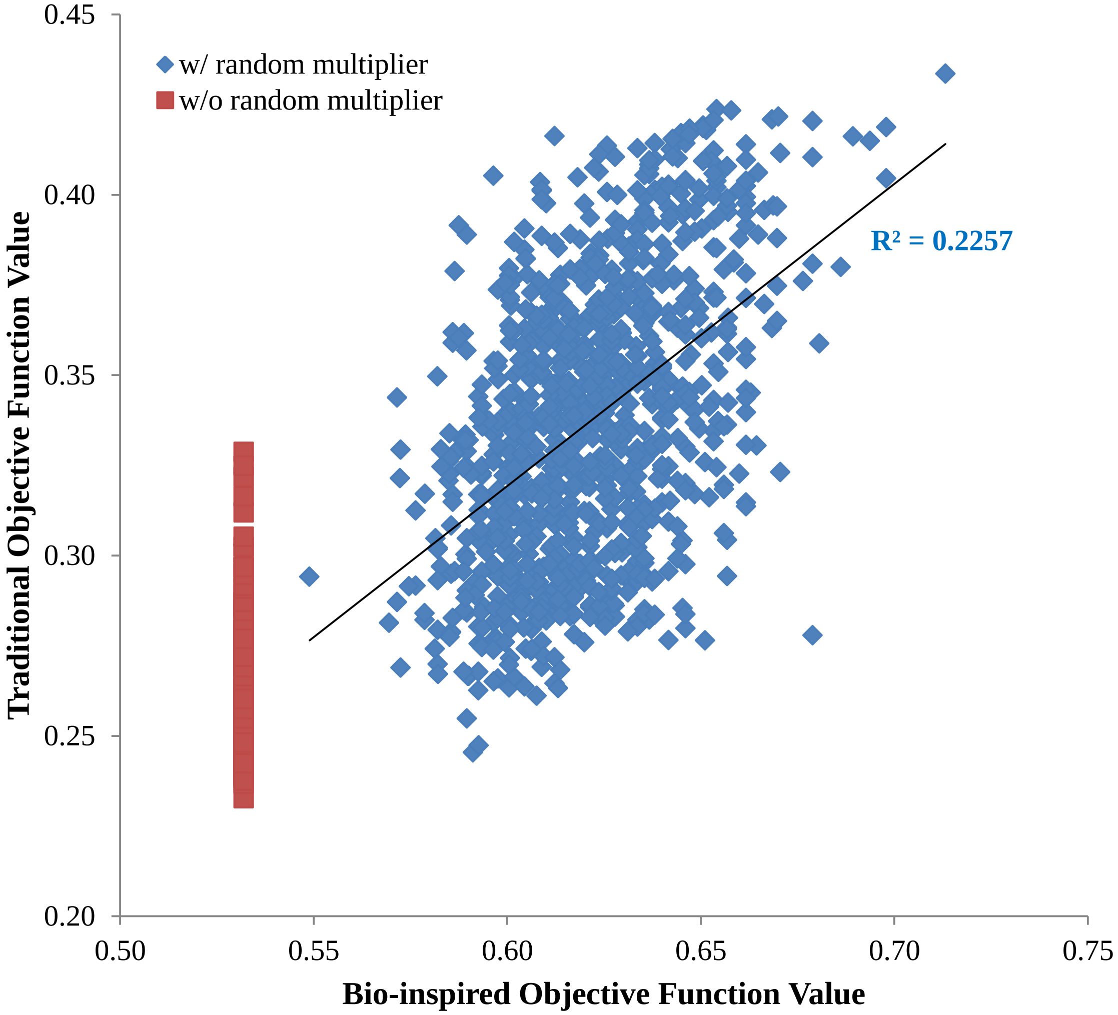


Figure 57: The relationship between the traditional and bio-inspired objective function values for 1000 random network designs. Only the 6 structural metrics were used to calculate $Z_{bio}$, excluding the flow metrics *CL* and *MPL*. The red (w/o random multiplier) was done using the original design generator. The blue diamonds (w/ random multiplier) used a randomly generated zero or one multiplier for each value in the design to reduce the original bias for a nonzero flow.

A potential solution to this issue is the multiplication of every value in the design by a randomly determined one or zero, increasing the chance of getting a value of zero (or no material flow) for one of the flows. This solves the issue of having a bias towards nonzero values of $x_{16}$ – $x_{41}$ and the resultant constant value of $Z_{bio}$ when only structural metrics are used, and from this point forward the design is always calculated using this random zero or one multiplier.

The correlation between traditional and bio-inspired goals using this new design selection process show only a weak effect is produced by changes in the structural metrics, as seen in Figure 57 by the behavior of the blue diamond-signifiers (w/ random multiplier). Figure 58 and Figure 59 run the same analysis as Figure 57 but this time adding the flow metric *CI* and then *MPL* to the 6 structural metrics. The strong effect that the flow based metrics *CI* and *MPL* have on the correlation between traditional and bio-inspired goals is clear: the $R^2$ value jumps up from 0.23 for only structural metrics (Figure 57) to 0.76 and 0.51 when *CI* and *MPL* are added respectively (Figure 58 and Figure 59 respectively). These three figures show a slight minimization in the dominance of *CI* and *MPL* on the objective function when the design is less prone to a nonzero flow. With the original bias towards an entirely nonzero design, the use of only the structural metrics results in no change in $Z_{bio}$ (red square signifiers in Figure 57) however the same design when used with *CI* and *MPL* in addition to the structural metrics do show a variation in $Z_{bio}$ (red square signifiers in Figure 58 and Figure 59 respectively).

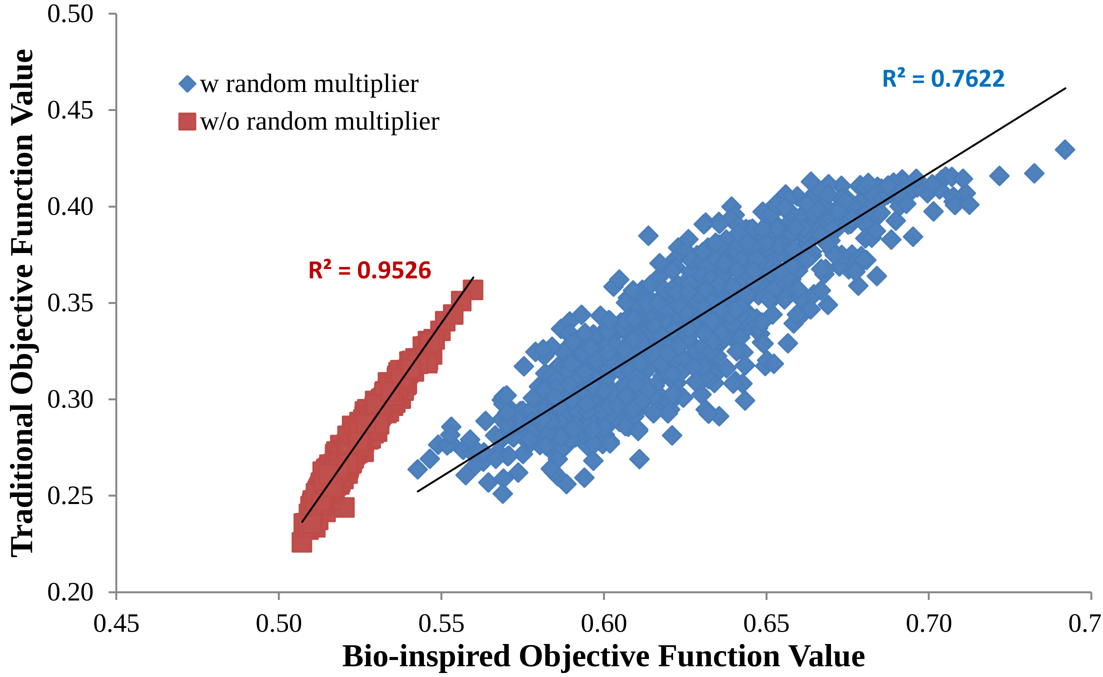


Figure 58: The relationship between the traditional and bio-inspired objective function values for 1000 random network designs. The flow metric cycling index (*CI*) was used with 6 structural metrics. The blue diamonds (w/ random multiplier) used a randomly generated zero or one multiplier for each value in the design to reduce the original bias for a nonzero flow.

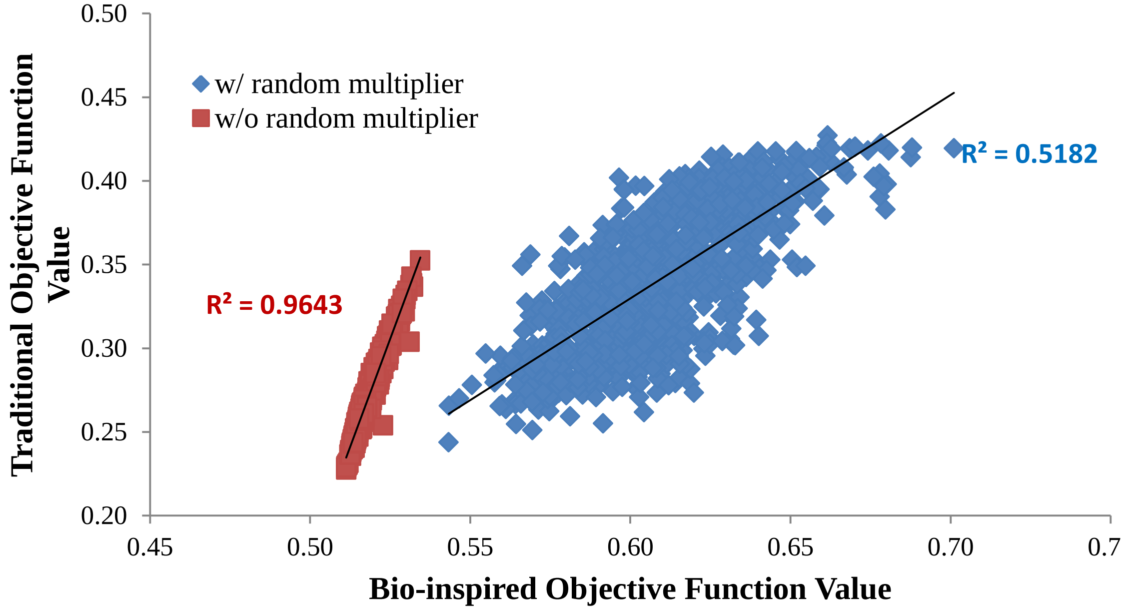


Figure 59: The relationship between the traditional and bio-inspired objective function values for 1000 random network designs. The flow metric mean path length (*MPL*) was used with 6 structural metrics. The blue diamonds (w/ random multiplier) used a randomly generated zero or one multiplier for each value in the design to reduce the original bias for a nonzero flow.

Figure 60 plots the relationship between $Z_{bio}$ and $Z_{trad}$ using four combinations of structural and flow metrics to calculate $Z_{bio}$. The results show that changes in the magnitude of the flow across the linkages ($Z_{bio}$ calculated using *CI* and/or *MPL*) still dominate the structural aspect of a link being turned on or off. The correlation between the traditionally determined objective function ($Z_{trad}$) and the bio-inspired objective function ($Z_{bio}$) decreases from a maximum of 0.83 when all 8 metrics are used (both flow and structural metrics) to a minimum of 0.23 when only the six structural metrics are used. To understand the underlying behavior causing the relative effect of the two metric, types further combinations are investigated.

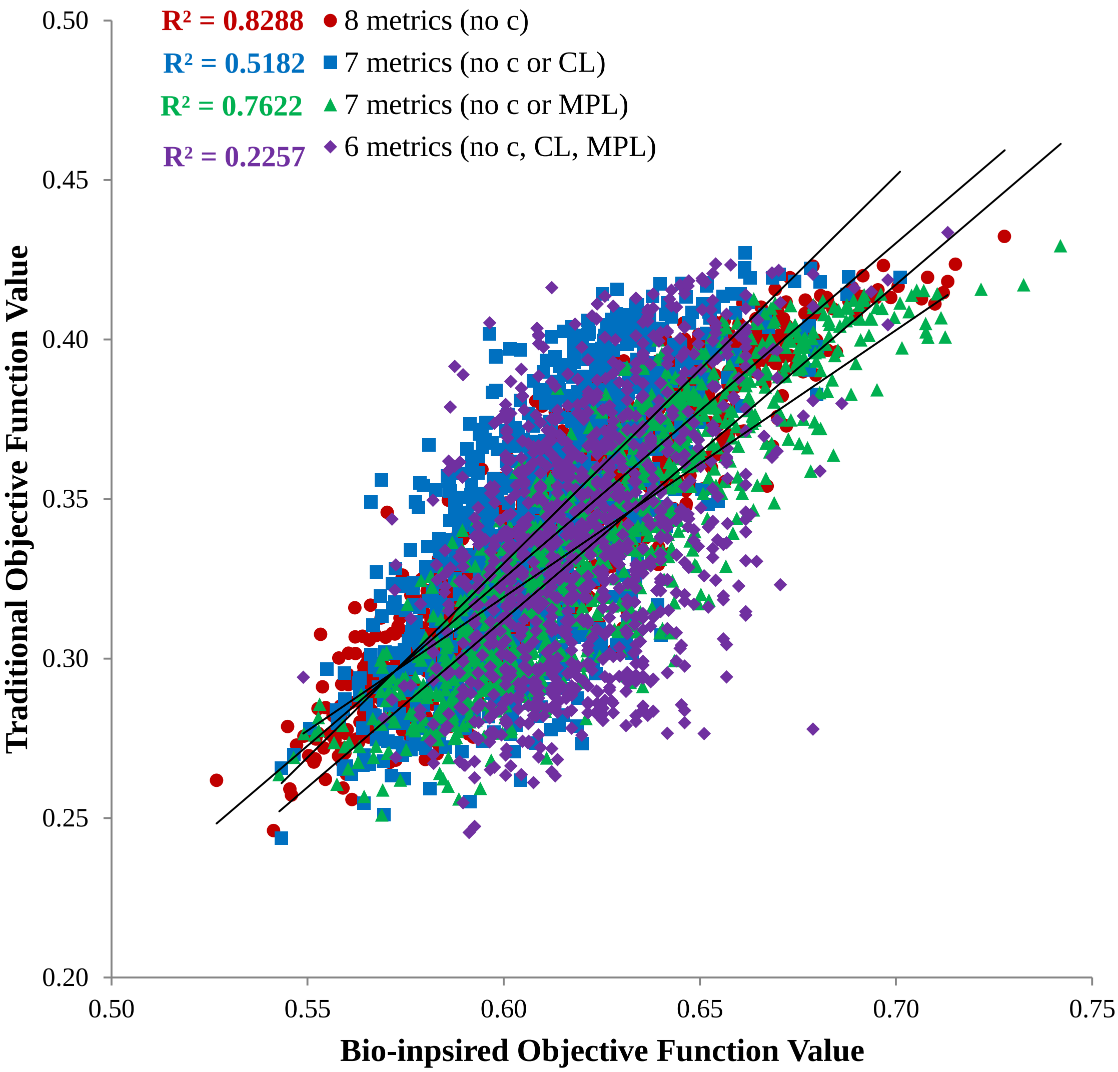


Figure 60: The relationship between the traditional and bio-inspired objective function values for 1000 random network designs. The four scenarios plotted here show clearly that the correlation found using all eight metrics is dominated by the metrics *CI* and *MPL*.

The flow metrics were further investigated in relation to the metric cyclicity, following the conclusions made earlier in this work that cyclicity is a very important structural metric in the design of bio-inspired networks. The same relationship as seen in Figure 57 through Figure 60 between $Z_{bio}$ and $Z_{trad}$ is repeated however. Figure 61 shows that when only cyclicity is used the worst correlation between the two types of objective functions results, and when *CI* and *MPL* are used together both with and without cyclicity the best correlations result.

Interesting to note however is that the correlation reached using only cyclicity $R^2 = 0.24$, is actually slightly better than the correlation reached using all six structural metrics $R^2 = 0.23$ in Figure 57. This supports the hypothesis that some food web metrics are more influential in the bio-inspired design of industrial networks than others.

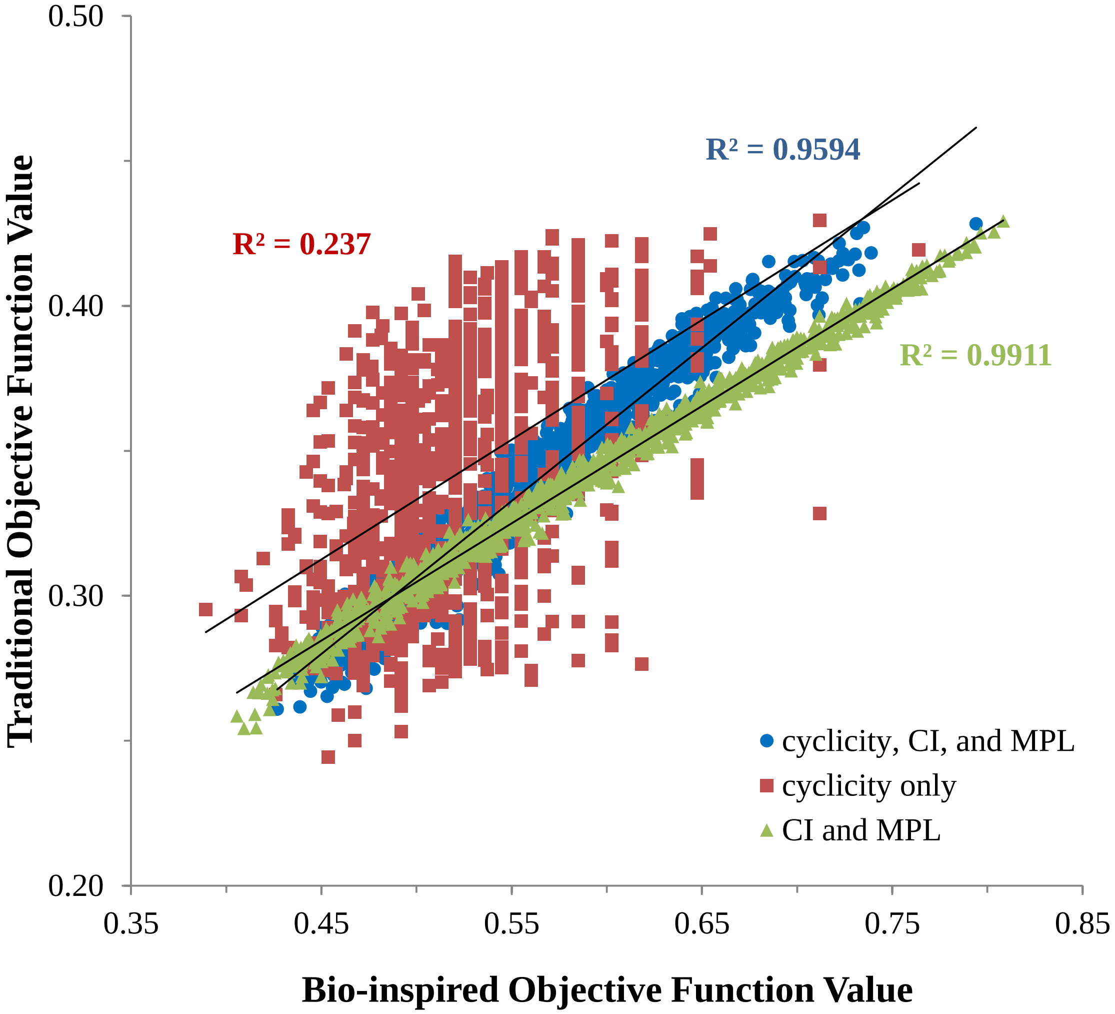


Figure 61: The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs. The three metrics cyclicity, cycling index, and mean path length are investigated. The three metrics were used together, cyclicity was run alone, and CI and MPL were run together. These three scenarios show clearly that the results seen in the first run (blue) with all three metrics, is dominated by the metrics CI and MPL.

The apparent irrelevance of the structural metrics shown in the previous trials, even when the design generator is adjusted to be unbiased in the assignment of a link as ‘on’ or ‘off’, is contrary to the rest of the work done in this dissertation: that *structure matters*. One hypothesis for the apparent domination of flow is that changes in the traditional objective function caused by changes in flow magnitude overwhelm any changes due to structural modifications (the assignment of a link as ‘on’ or ‘off’). This suggests that there is a bias in the traditional objective function towards flow-based changes. This bias is most likely due to the relative environmental impact, one of the components in the calculation of $Z_{trad}$, of changes in the amounts of recycling and reuse, for example a larger usage of used carpet results in a smaller environmental impact.

To adjust for this bias, preset flow magnitudes for the entire design are selected, so that the only differences between designs are in the designation of active and inactive linkages. The use of preset magnitudes limits changes in the traditional objective function due to changes in flow magnitude. This new set up allows the focus to be on whether or not a linkage is ‘on’ or ‘off’ (on being a one multiplier and off being a zero multiplier). The flows from the best design found by Reap’s initial analysis are initially tested. This design has different magnitudes of carpet flowing across different linkages and so this selection does not fully adjust for the effect of flow on the traditional objective function, as the relative magnitudes of $x_{16} – x_{41}$ provide different reductions to the resultant environmental impact.

To address this issue, the magnitudes of $x_{16} – x_{41}$ are set such that they process equivalent volumes of used carpet when a link is active. The value chosen for the design may not violate any of the flow constraints, and so the smallest value among the maximum flow constraints as set by the model is used: 8268 kg/yr of carpet. This preset value coupled with the randomized on/off switch (one or zero multiplier) now provides an unbiased evaluation of the effect of both flow and structural metrics.

## 9.4 Analyses of Metrics: Mortem and Redivivus of Structure

"Movement gives shape to all forms. Structure gives order to movement."

— Leonardo da Vinci (paraphrased in (Bohm 1998))

The objectives of the various analyses run here on the carpet recycling network model are as follows:

- Investigate a possible dominance of some food web metrics over others in the resultant bio-inspired design configuration. The effect of each individual metric by itself on the resultant design will be compared against using all eight metrics together, as well as all other possible combinations of the metrics.
- Isolate the structure-based food web metrics and the flow-based food web metrics to investigate the effects each has in controlling the resultant network design.
- Apply the newly investigated flow-based food web metrics from chapter 8 to the carpet recycling model to gain insight into the possible uses for flow-based metrics in the design of EIPs and other industrial networks.

The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs are investigated for each of the eight food web metrics in Table 40 individually, as well as using all eight metrics and all six structural metrics. Figure 62 illustrates the results. The improvement of certain food web metrics clearly has a stronger correlation to the minimization of emissions and costs for the network, represented by improvements in the bio-inspired and traditional objective functions respectively. Improvements in $Z_{bio}$ (decreases) calculated from $\lambda_{max}$, $G$, and $V$ result in larger improvements in $Z_{trad}$ (decreases) as shown by their flatter slopes in comparison to the other metrics. The metrics $P_R$, $\lambda_{max}$, $P_S$, and $V$ all have the worst correlations when used individually between $\mathrm{Z_{bio}}$ and $Z_{trad}$. The $R^2$ values correlating $Z_{trad}$ values to $Z_{bio}$ are shown in Table 41. The values from best to worst for the eight metrics are: $CI > MPL > G > L_D > P_R > \lambda_{max} > P_S, > V$ ranging from 0.96 to 0.32 respectively. The $R^2$ values for the runs using all eight metrics and all six structural metrics fall in between the values for *MPL* and *G* at 0.89 and 0.88. Thus when all the metrics are used together (all 8 and all 6 structural metrics) the correlation is strong. This poses the hypothesis that the food web metrics may work best in groups, balancing any extreme effects due to any one individually.

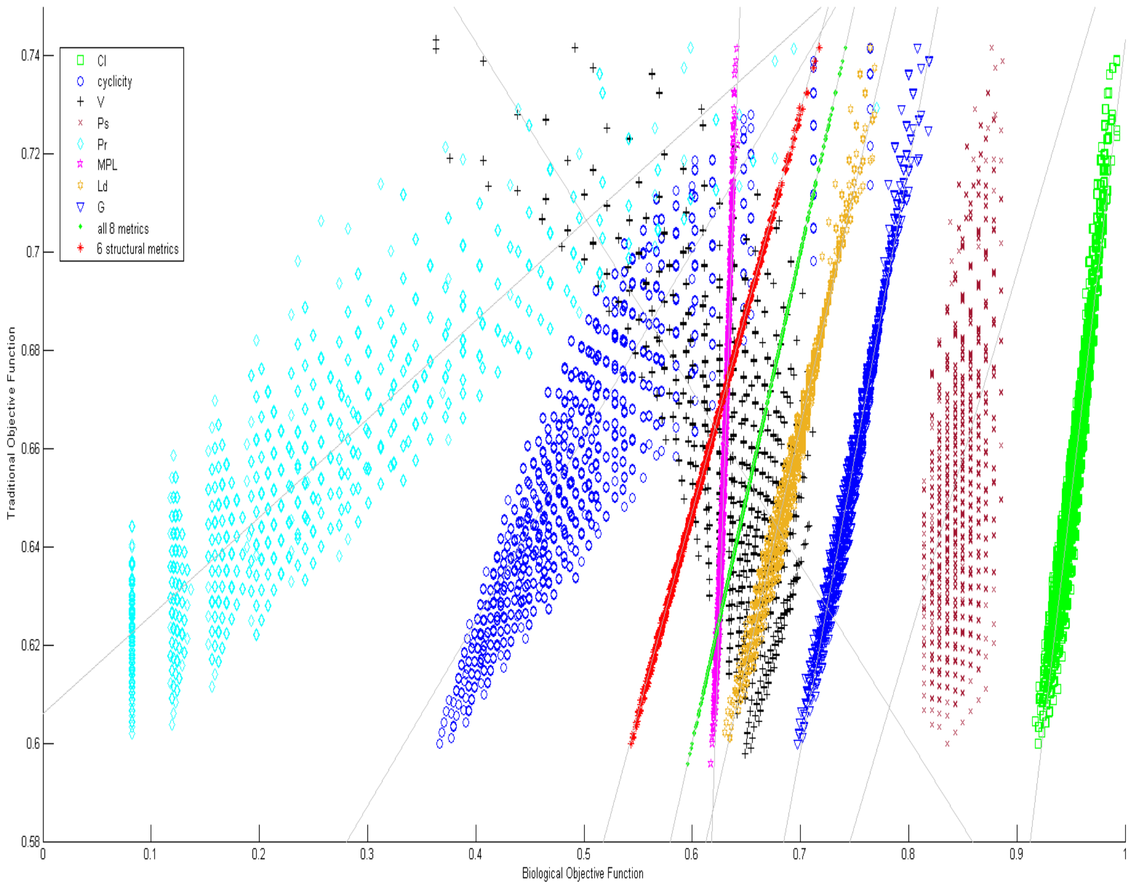


Figure 62: The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs. The flow amount for each link in the design vector was held constant at 8268 kg/yr of carpet.

Table 41: $R^2$ values for the linear relationship between $Z_{bio}$ and $Z_{trad}$ for the trials investigated in Figure 62.

| | $R^2$ for $Z_{bio}$ vs. $Z_{trad}$ |
|---|---|
| **CI** | *0.960* |
| **MPL** | *0.908* |
| **All 8 Metrics** | *0.886* |
| **All 6 Structural Metrics** | *0.876* |
| **G** | *0.834* |
| **Ld** | *0.833* |
| **Pr** | *0.733* |
| **cyclicity** | *0.581* |
| **Ps** | *0.477* |
| **V** | *0.316* |

Figure 63 investigates different groupings of the tested metrics to see if there is an additive or subtractive effect when combining them. The testing of different metric groupings led to a group of metrics that outperformed the rest: generalization, prey to predator ratio, specialized predator fraction, and cyclicity ($G$, $P_R$, $P_S$, and $\lambda_{max}$). Minimization of the objective function made up of this group correlates with an $R^2$ value of 0.87 with minimizations of the traditional objective function. Using only four structural metrics the network can be optimized for both cost and emissions and at the same time mimicking the structure of food webs. For comparison, the $R^2$ value of all eight metrics was 0.89 and for all six structural metrics was 0.88 as plotted in Figure 62.

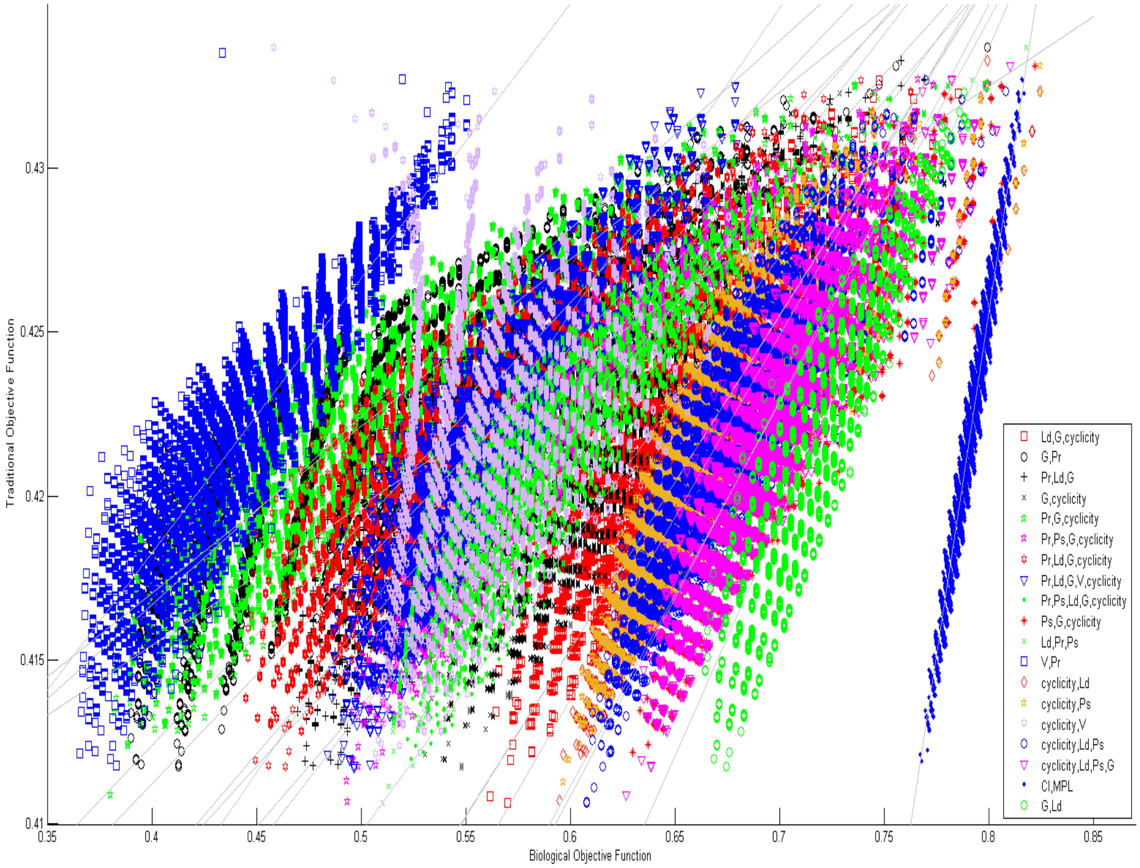


Figure 63: The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs that explore different combinations of structural food web metrics. The flow amount for each link in the design vector was held constant at 8268 kg/yr of carpet.

The objective functions plotted here are calculated based on only the metrics chosen, so $Z_{\text{bio}}$ for $P_S$ and $G$ is calculated from the success that the network has in matching food web median values of $P_S$ and $G$. The different groups of metrics tested in Figure 63 all minimize their own bio-inspired objective function as expected, their correlation with reductions in the traditional objective function vary though.

To see how effectively any of the selected food web metrics are at matching the target values for all the other food web metrics, a total bio-inspired objective function ($Z_{bio,total}$) based on all 8 metrics is calculated for each set of simulations run in Figure 62 and Figure

63. Figure 64 compares the success that each group has in minimizing $Z_{bio,total}$,. The minimum $Z_{bio,total}$ value obtained from all 29 different food web metric combinations investigated, those shown in Figure 62 and Figure 63, do not show much variance contrary to what they initially suggest from the different $Z_{bio}$ values. All 29 metric sets tested resulted in similar minimum traditional objective functions as well. Thus choosing the best group to use for design guidance based on the correlation between $\mathrm{Z}_{\mathrm{bio}}$ and $Z_{trad}$ will result in a minimized $Z_{bio,total}$ as well and therefore is the best choice for network designers.

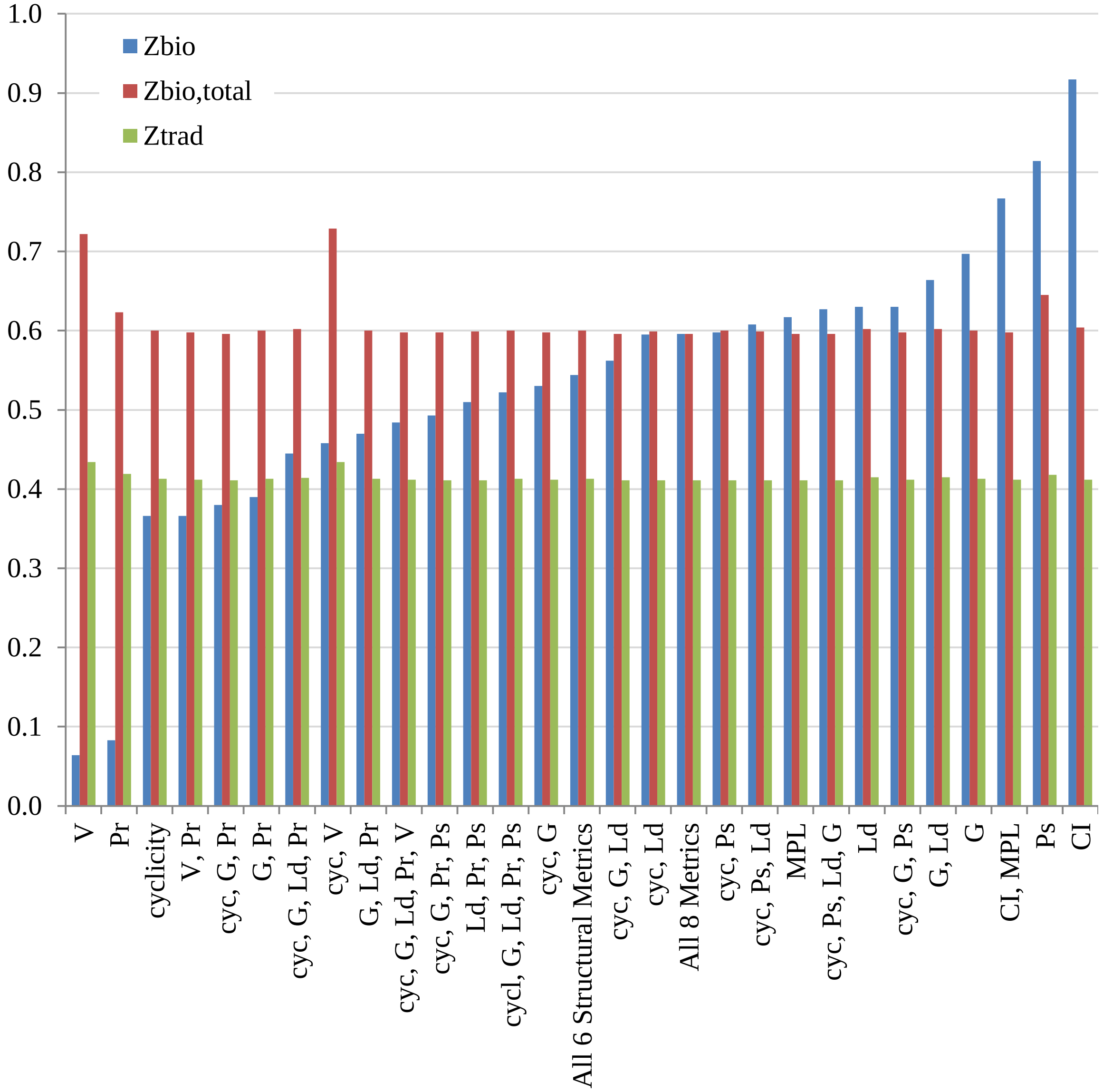


Figure 64: Minimum objective function values based on traditional metrics (Ztrad), selected food web metrics (*Zbio*) and all 8 investigated food web metrics (*Ztot,bio*).

All other things equal, a best combination of food web metrics arises for minimizing both the bio-inspired and traditional objective functions. The combination is made up of four structural metrics: generalization, prey to predator ratio, specialized predator fraction, and cyclicity ($G$, $P_R$, $P_S$, and $\lambda_{max}$) and results in a $R^2$ value of 0.872 correlating minimizations of the biological and traditional objective functions. Figure 65 focuses on this best combination of metrics, showing the behavior of the objective functions when these four metrics are used, as compared to when all 8 metrics and all 6 structural metrics are used. The four metrics when used together reach essentially the same correlation result between $Z_{bio}$ and $Z_{trad}$ as when all six structural metrics are used ($R^2 = 0.876$). The correlation obtained from these four metric is also very close to the correlation obtained from all eight metrics ($R^2 = 0.886$).

That the correlation using four structural metrics would come so close to the correlation using all 8 structural and flow metrics is a result that was unexpected following the initial testing of the model (Figure 60 and Figure 61 especially), when the use of only structural metrics did not come close to matching the performance when the two flow metrics were added.

That the best correlation would be made up of $G$, $P_R$, $P_S$, and $\lambda_{max}$ is also unexpected following the testing of the individual metrics. The results of individual metric tested in Figure 62 shows that the metrics specialized predator fraction and cyclicity both have poor performance when used alone - generating two of the worst correlations between the objective functions $\mathrm{Z_{bio}}$ and $\mathrm{Z_{trad}}$ with $R^2$ values of 0.467 and 0.596. When $\lambda_{max}$ and $P_S$ are used together with $P_R$ and $G$ however outperform all other groupings of metrics and individual metrics.

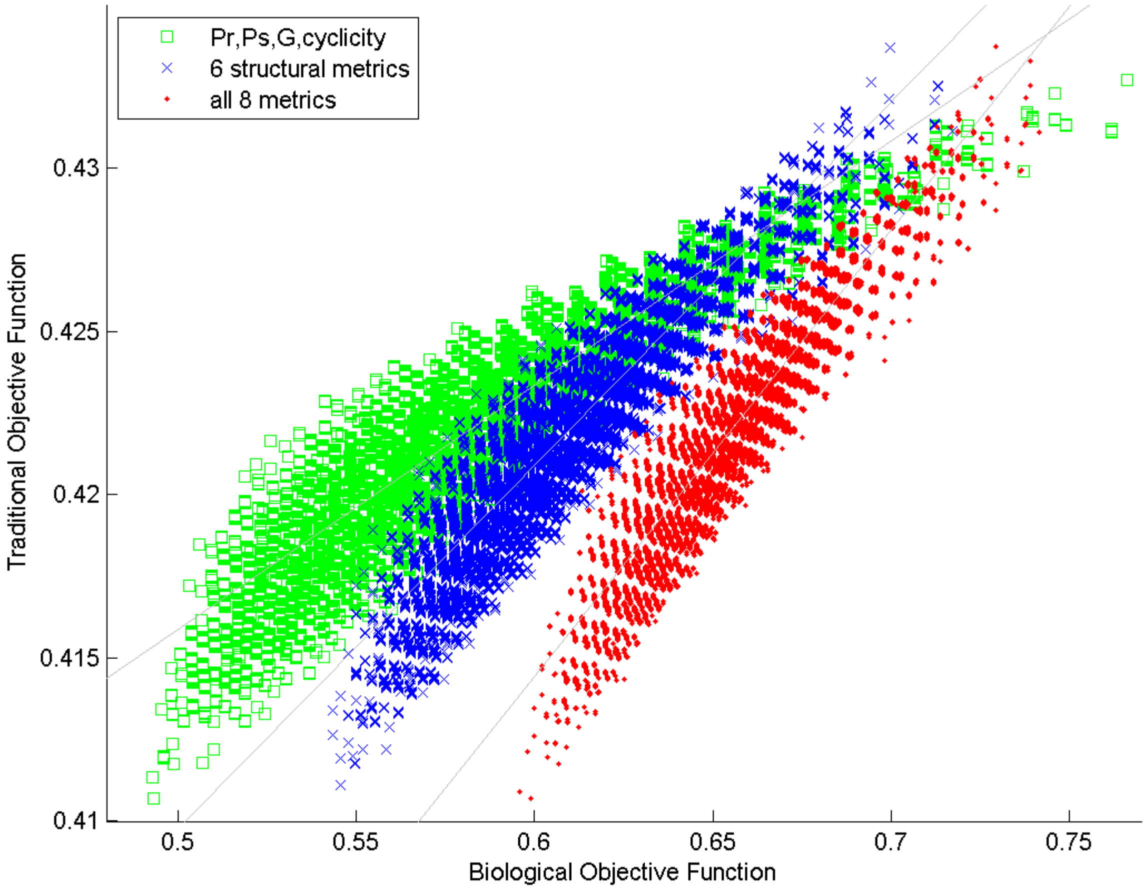


Figure 65: The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs. The top scenario is investigated and compared to the use of all the metrics. The four structural metrics: generalization ($G$), specialized predator fraction ($P_S$), prey to predator ratio ($P_R$), and cyclicity were used together. The flow amount for each link in the design vector was held constant at 8268 kg/yr of carpet, the minimum upper bound in the design vector.

### 9.5 Design Proposal: A Two Step Optimization

How can the food web metrics best be used to optimize industrial resource networks, and specifically the carpet recycling network investigated here? The four metrics generalization, specialized predator fraction, prey to predator ratio, and cyclicity ($G$, $P_S$, $P_R$, and $\lambda_{max}$) can only determine the structure of a network. These metrics have no influence on flow magnitudes, and so once the structure has been established the flow must still be determined. The previous optimizations were done using a constrained flow value of 8268 kg/yr for each link. Another round of optimizations are run using a structure determined by the four selected structural metrics but allowing for the flows to be optimized. The flow optimization is done based on the traditional objective function $Z_{trad}$ that minimizes cost and 12 emissions for the entire network. Figure 66 shows the results for this two-step process. The structure is chosen based on the "best point" from the correlation between $Z_{trad}$ and $Z_{bio}$ calculated from the four best structural metrics. Three of the structures tested are listed in Table 42. Holding this structure constant, the optimization was re-run allowing flows to optimize (step two) to further minimize the $Z_{trad}$.

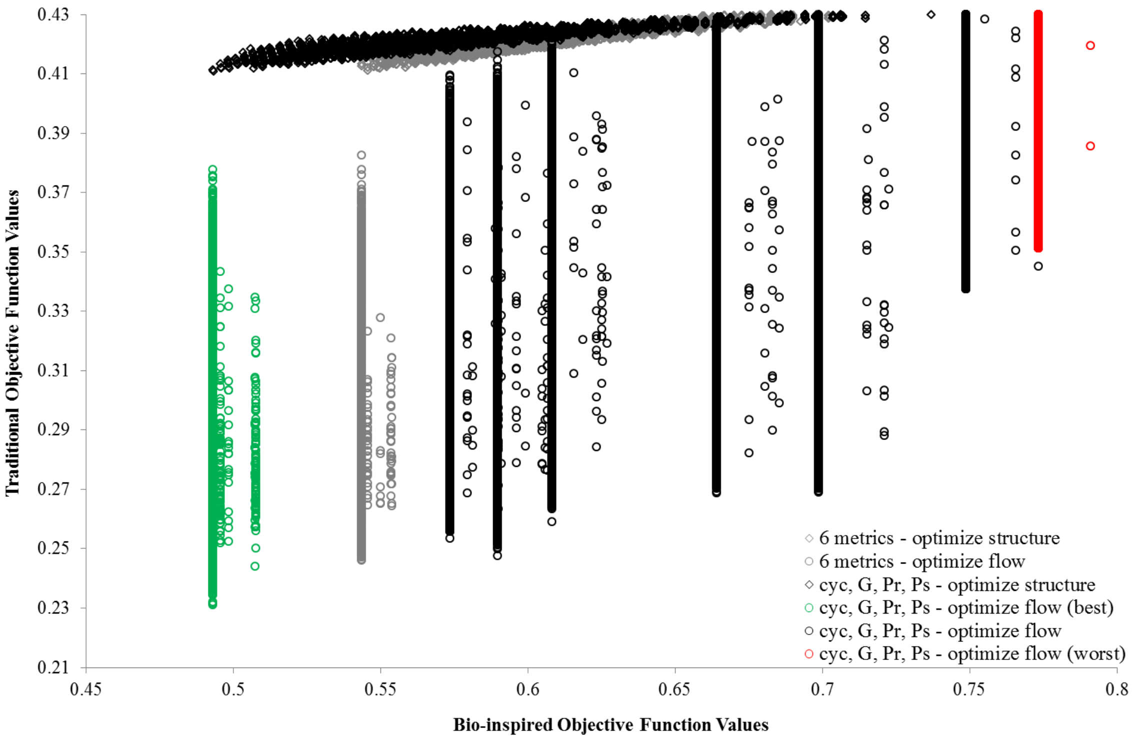


Figure 66: The relationship between the traditional and bio-inspired objective function values for 100,000 random network designs. The runs were done using the combination of $G$, $P_R$, $P_S$, and $\lambda_{max}$ to find an optimal structure for the carpet recycling network (blue diamonds). From the best structure (minimum Bio objective function value found) the traditional objective function was minimized to find the optimal flows for the design vector (green circles). The worst strucure (maximum Bio objective function value) was also used to minimize the traditional objective function value (red circles), as well as various structures in between the min and max Bio objective function values (black circles).

The structure for both the minimum and maximum biological objective function $Z_{bio}$ calculated using the four best design metrics found in section 9.4 ($G$, $P_S$, $P_R$ and $\lambda_{max}$) were tested. Six randomly chosen structures between these two extremes were also tested. The results plotted in Figure 66 show that the 'best' structure determined by the four metrics $G$, $P_S$, $P_R$ and $\lambda_{max}$ results in the 'best' carpet recycling network from both a traditional and a biological viewpoint. The results also show that the better structures (in terms of being more biological i.e. lower $Z_{bio}$) tend to produce a better overall network ('overall' includes material and/or energy flows i.e. $Z_{trad}$). Thus the food web structural metrics have merit in determining an overall best structure, despite flow based changes dominating the final system design.

To test the proposal here that the four metrics ($G$, $P_S$, $P_R$ and $\lambda_{max}$) used in a two-step optimization result in the best network design both from a biological standpoint and a traditional industry standpoint the use of all six structural metrics is also tested. Figure 66 plots the two-step optimization procedure using all six structural metrics (using $V$ and $Ld$, in addition to $G$, $P_S$, $P_R$ and $\lambda_{max}$) to determine structure (grey circles). It is clear from the results plotted here that the six structural metrics do not produce a structure as biologically optimal as the four. This structure then restricts the traditional optimization when flows are added to a higher value (a lower $Z$ value comes closer to meeting goals established).

Table 42 lists structural-information based food web metrics calculated for three different carpet recycling network setups: the best combination ($G$, $P_S$, $P_R$, and $\lambda_{max}$), from all eight metrics, and from all six structural metrics. The post 1993 food webs values for the same metrics are shown alongside the carpet network results for comparison. Table 42 lists the structure for the three network setups that lead to the results of Table 43 and Table 44 . Ones represent an active link in the design vector and a zero represents an inactive link.

Table 42: The best structure design vector, as determined by 100,000 random network designs. All flows in the design were held constant at the minimum upper bound for the set (8268 kg/yr of carpet).

| *Structural Design Vector* | **Model values for system determined using $\lambda_{max}$, $P_S$, $P_R$, and $G$ ($R^2$ = 0.87, $Z_{bio,total}$ = 0.51, $Z_{trad}$ = 0.26)** | **Model values for system determined using 6 structural metrics ($R^2$ = 0.88, $Z_{bio,total}$ =0.53, $Z_{trad}$ =0.31)** | **Model values for system determined using all 8 metrics ($R^2$ = 0.89, $Z_{bio,total}$ = 0.60, $Z_{trad}$ = 0.22)** | **Model values for traditional optimization ($Z_{bio,total}$ = 0.53, $Z_{trad}$ = 0.20)** |
|---|---|---|---|---|
| $x_{16}$ | *1* | *1* | *1* | *0* |
| $x_{17}$ | *1* | *1* | *1* | *0* |
| $x_{18}$ | *1* | *1* | *1* | *1* |
| $x_{19}$ | *1* | *1* | *1* | *1* |
| $x_{20}$ | *1* | *1* | *1* | *0* |
| $x_{21}$ | *1* | *1* | *1* | *1* |
| $x_{22}$ | *1* | *1* | *1* | *1* |
| $x_{23}$ | *1* | *1* | *1* | *0* |
| $x_{24}$ | *1* | *1* | *1* | *0* |
| $x_{25}$ | *1* | *1* | *1* | *0* |
| $x_{26}$ | *1* | *1* | *1* | *0* |
| $x_{27}$ | *1* | *1* | *1* | *0* |
| $x_{28}$ | *1* | *1* | *1* | *0* |
| $x_{29}$ | *0* | *1* | *1* | *1* |
| $x_{30}$ | *1* | *1* | *1* | *1* |
| $x_{31}$ | *0* | *1* | *1* | *1* |
| $x_{32}$ | *0* | *0* | *0* | *1* |
| $x_{33}$ | *1* | *1* | *1* | *1* |
| $x_{34}$ | *1* | *0* | *1* | *1* |
| $x_{35}$ | *1* | *1* | *1* | *1* |
| $x_{36}$ | *1* | *1* | *1* | *1* |
| $x_{37}$ | *1* | *0* | *1* | *1* |
| $x_{38}$ | *1* | *1* | *1* | *1* |
| $x_{39}$ | *1* | *0* | *0* | *1* |
| $x_{40}$ | *0* | *0* | *0* | *1* |
| $x_{41}$ | *0* | *0* | *0* | *1* |

Table 43: Food web structural metrics for the best network design for each specified run, as determined by 100,000 random designs. The first three specified runs using food web metrics set all flows in the design to a constant 8268 kg/yr of carpet, then held the structure constant (that associated with the best $Z_{bio}$ value) to optimize the flow. The "traditional optimization only" run solution is the result of a constrained linear optimization.

| *Food Web Metrics* | **$\lambda_{max}$, $P_S$, $P_R$, and $G$** | **6 structural metrics** | **8 original metrics** | **Traditional Optimization Only** | **Median Post 1993 Food Webs** |
|---|---|---|---|---|---|
| **$N$** | *24* | *24* | *23* | *29* | *51* |
| **$L$** | *45* | *45* | *43* | *46* | *249* |
| **$L_d$** | *1.88* | *1.88* | *1.87* | *1.59* | *5.04* |
| **$N_{prey}$** | *24* | *24* | *23* | *29* | *41* |
| **$N_{predator}$** | *24* | *24* | *23* | *29* | *38* |
| **$P_R$** | *1* | *1* | *1* | *1* | *1.09* |
| **$N_{S\text{-}predator}$** | *14* | *14* | *14* | *14* | *3* |
| **$P_S$** | *0.583* | *0.583* | *0.609* | *0.483* | *0.10* |
| **$G$** | *1.88* | *1.88* | *1.87* | *1.59* | *6.18* |
| **$V$** | *1.88* | *1.88* | *1.87* | *1.59* | *5.34* |
| **$c$** | *0.078* | *0.078* | *0.081* | *0.055* | *0.152* |
| **$\lambda_{max}$** | *2.70* | *2.70* | *0.191* | *2* | *4.24* |

Table 44: Objective function values for the best network design for each specified run, as determined by 100,000 random designs. The first three specified runs using food web metrics set all flows in the design to a constant 8268 kg/yr of carpet, then held the structure constant (that associated with the best $Z_{bio}$ value) to optimize the flow. The "traditional optimization only" run solution is the result of a constrained linear optimization. $R^2$ values are associated with the first step of this process, the rest of the values are associated with the second.

| | **$\lambda_{max}$, $P_S$, $P_R$, and $G$** | **6 structural metrics** | **8 original metrics** | **Traditional Optimization Only** |
|---|---|---|---|---|
| **$Z_{trad}$** | *0.26* | *0.31* | *0.60* | *0.20* |
| **$Z_{bio}$** | *0.49* | *0.54* | - | - |
| **$Z_{bio,total}$** | *0.51* | *0.53* | *0.60* | *0.53* |
| **$R^2$** | *0.87* | *0.88* | *0.89* | - |

## 9.6 Flow Metric Investigation

The flow metrics cycling index (*CI*) and mean path length (*MPL*) used in the carpet recycling network problem show that flow metrics can very effectively be used to optimize industrial networks for both traditional and biological goals. *CI* and *MPL* individually produced a correlation far better than what six structural metrics could do in all the previous scenarios, and the two when used together resulted in the best correlation, with an $R^2$ value of 0.99 in Figure 61. The preliminary studies of additional flow-information food web metrics in chapter 8 strongly suggest that these metrics can be very useful in the design of industrial resource networks.

Table 45 shows the nine flow-information food web metrics for scenarios of the two-step optimizations using the best structural combination of metrics ($\lambda_{max}$, $P_S$, $P_R$, and $G$) from Figure 66. Metrics were calculated following the methods and equations outlined in section 8.3. This selection of cases highlights changes in the flow metrics as the traditional and biological objective functions are improved.

Table 45: Flow-based food web metrics for configurations of the carpet recycling network (optimized for flow) found using structures determined by the four metrics $G$, $P_S$, $P_R$, and cyclicity. The best structure, worst structure, and six randomly chosen structures in between are shown here (scenarios correlate with those plotted in Figure 66).

| | Post 1993 Food Web Medians | Best Structure | Worst Structure | Random Middle Structures | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **$Z_{BIO}$** | - | 0.493 | 0.774 | 0.574 | 0.590 | 0.608 | 0.664 | 0.699 | 0.749 |
| **$Z_{TRAD}$** | - | 0.263 | 0.402 | 0.314 | 0.328 | 0.322 | 0.352 | 0.408 | 0.377 |
| **$Z_{BIO,TOTAL}$** | - | 0.513 | 0.718 | 0.580 | 0.602 | 0.610 | 0.645 | 0.702 | 0.701 |
| ***CI*** | 0.104 | 0.168 | 0.041 | 0.131 | 0.117 | 0.117 | 0.094 | 0.028 | 0.068 |
| ***MPL*** | 2.67 | 3.30 | 2.28 | 2.95 | 2.82 | 2.84 | 2.65 | 2.18 | 2.45 |
| ***AMI*** *(w/ k=1)* | 1.74 | 2.34 | 2.65 | 2.49 | 2.52 | 2.56 | 2.54 | 2.67 | 2.66 |
| ***ASC*** *(x$10^{6}$)* | 0.0181 | 19.4 | 19.8 | 20.2 | 20.2 | 20.5 | 19.9 | 19.6 | 20.4 |
| ***DC*** *(x$10^{6}$)* | 0.0395 | 40.6 | 33.6 | 37.5 | 37.4 | 37.2 | 36.4 | 33.0 | 34.8 |
| ***TSO*** *(x$10^{6}$)* | 0.0207 | 4.55 | 1.55 | 3.98 | 3.57 | 3.50 | 3.03 | 0.714 | 2.29 |
| ***TSTp*** *(x$10^{6}$)* | 0.0109 | 8.28 | 7.48 | 8.10 | 7.99 | 7.97 | 7.84 | 7.32 | 7.65 |
| ***ASC/DC*** | 0.372 | 0.477 | 0.590 | 0.539 | 0.540 | 0.550 | 0.547 | 0.592 | 0.585 |
| ***R*** *(w/ k=1)* | 0.523 | 0.510 | 0.449 | 0.481 | 0.480 | 0.474 | 0.476 | 0.447 | 0.452 |

Table 46: Structure-based food web metrics for different configurations of the carpet recycling network (optimized for flow) found using structures determined by the four metrics $G$, $P_S$, $P_R$, and cyclicity. The best structure, worst structure, and six randomly chosen structures in between are shown here (scenarios correlate with those plotted in Figure 66).

| | Post 1993 Food Web Medians | Best Structure | Worst Structure | Random Middle Structures | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **$N$** | *51* | *24* | *21* | *21* | *19* | *25* | *19* | *18* | *21* |
| **$L$** | *249* | *45* | *34* | *32* | *26* | *47* | *24* | *21* | *31* |
| **$L_d$** | *5.04* | *1.88* | *1.62* | *1.52* | *1.37* | *1.88* | *1.26* | *1.17* | *1.48* |
| **$N_{prey}$** | *41* | *24* | *17* | *17* | *11* | *25* | *10* | *8* | *16* |
| **$N_{predator}$** | *38* | *24* | *21* | *21* | *19* | *25* | *19* | *18* | *21* |
| **$P_R$** | *1.09* | *1* | *0.81* | *0.81* | *0.579* | *1* | *0.526* | *0.444* | *0.762* |
| **$N_{S\text{-}predator}$** | *3* | *14* | *14* | *14* | *14* | *14* | *14* | *15* | *14* |
| **$P_S$** | *0.10* | *0.583* | *0.667* | *0.667* | *0.737* | *0.56* | *0.737* | *0.833* | *0.667* |
| **$G$** | *6.18* | *1.88* | *1.62* | *1.52* | *1.37* | *1.88* | *1.26* | *1.17* | *1.48* |
| **$V$** | *5.34* | *1.88* | *2.00* | *1.88* | *2.36* | *1.88* | *2.40* | *2.63* | *1.94* |
| **$c$** | *0.152* | *0.078* | *0.077* | *0.073* | *0.072* | *0.075* | *0.066* | *0.065* | *0.070* |
| **$\lambda_{max}$** | *4.24* | *2.70* | *2.33* | *2.13* | *1.93* | *2.70* | *1.62* | *1.22* | *2.03* |

## 9.7 Discussion

### 9.7.1 Reflections on Previous Findings for the Carpet Recycling Network

The findings of this chapter, specifically that of the dominance of the flow metrics cycling index (*CI*) and mean path length (*MPL*) for the original model as used by Reap, shows that the findings of Reap relating to Figure 46 presents a correlation between a bio-inspired design using *CI* and *MPL* and a traditionally optimized network. The two flow metrics both provide a very strong and highly correlated linear relationship between the biologically inspired network design and the traditionally optimized network design (as seen in Figure 61 showing an $R^2$ value of 0.99 between the biological and traditional objective functions when using *CI* and *MPL* alone). This is a much narrower finding than originally believed: one between the traditional network and a bio-inspired design using nine food web metrics (*CI*, *MPL* and 7 structural metrics).

Two major biases existed in the original code: the first was towards choosing a number other than zero for the quantity of flow across a linkage and the second was a dominance of changes due to flow over those due to structure. Modifying the code to account for these two biases resulted in a 'strongest combinations' made up of four structural metrics: a combination of cyclicity, specialized predator fraction, prey to predator ratio, and generalization. Vulnerability was found to have very little to no significant positive effect on the correlation with regards to the minimization of the traditional objective function. Linkage density when used on its own showed a relatively good correlation with minimization of the traditional objective function ($R^2$ of 0.83), however when used in combination it did not contribute as strongly as the other metrics, and actually reduced the correlation when used in conjunction with the 'best' four structural metrics. The best combination ($\lambda_{max}$, $P_S$, $P_R$, and $G$) had an $R^2$ value of 0.88 between $Z_{bio}$ and $Z_{trad}$ when 100,000 random network designs at 100% recycling efficiency were compared. Holding the flow constant at the smallest max-constraint in the design vector (a carpet flow of 8268 kg/yr) reduces the influence on the biological objective function that changes in flow have. Large changes in flow still dominate structural changes in terms of $Z_{bio}$ however the findings here do conclude that structure is important.

### 9.7.2 Best Performing Combination

The findings of section 9.5 present the question, what is it about these four metrics ($G$, $P_R$, $P_S$, and $\lambda_{max}$) together that result in such a good correlation? The performance of any of them alone is not particularly special, and when they are used in combination with the other structural metrics no magic happens either.

Cyclicity has already been studied in depth throughout this dissertation; see chapter 4 and sections 3.3.2, 3.3.2, 3.5.2, 6.4.1, and 5.4.2. Cyclicity in food webs is directly related to indirect effects, whose dominance has been found to be characteristic of ecosystems (see sections 2.3.3 and 6.4.1). Cyclicity is a measurement of the pathway proliferation rate, which is enabled by the detritus and decomposers actors in the system. Cyclicity as related to EIPs draws parallels to how efficiently the materials and energy in the system are used before they leave circulation (see section 4.2.2 and 4.4). Generalization, prey to predator ratio, and specialized predator fraction all relate to feeding relationships, or how the actors in the system interact. Generalization is the number of prey species that a species can consume (Pimm 1982, Schoener 1989). The prey to predator ratio is representative of the number of producers available per consumer, a number greater than one represents an abundance of production and a number less than one a scarcity. The specialized predator fraction is the fraction of predators that only feed on only one type of species, or are specialized. Section 5.4.2: Cyclicity and the Detritus Actor discusses the percentage of specialized actors in a system and the affect the percentage has on the system’s ability to achieve a level of cyclicity comparable to what is seen on average in food webs.

Network symmetry is affected by the presence of specialized predators and generalists and the total ratio of prey to predators. Generalists have been shown to act as the backbone in food webs allowing for rare species and specialists to exist, contributing to the asymmetric structure characteristic of ecosystems (Bascompte, Jordano et al. 2003, Bascompte and Jordano 2007). A high degree of asymmetry in food webs has been linked to enhancements in long-tern coexistence and the maintenance of biodiversity (Bascompte, Jordano et al. 2006, Vazquez, Melian et al. 2007). These four metrics together then monitor the presence and strength of cycling in the system, the levels of specialized vs general actors, and the availability of resources for consumers. Together they encompass both system structure and function.

The success of the two step process begs the question; can this analysis be done in one step? To test this question the three structural metrics $G$, $P_S$, $P_R$, and $\lambda_{max}$ were used to calculate *Zbio* so that flow was simultaneously allowed to vary, as opposed to being held constant at 8268 kg/yr as in the previous 2-step process. Figure 57, Figure 60, and Figure 61 however are proof that the success of the two step process cannot be replicated by combining the search for a bio-inspired structure with the determination of flow.

### 9.7.3 Behavior of Flow-Based Food Web Metrics

As discussed in section 8.6, the flow metrics can be organized into dimensional metrics and non-dimensional groups. The dimensional metrics (*TSTp*, *ASC*, *DC*, and *TSO*) tend to vary by a factor of 10 at the least between median values for food webs and industrial network values. This variation in scale makes using the dimensional metrics in comparisons difficult. Figure 67 highlights the changes in the nondimensional flow metrics (*CI*, *MPL*, *AMI*, *ASC*/*DC*, and *R*) as the carpet recycling network minimizes both a traditional objective function and a biological objective function based on the best combination of structural metrics.

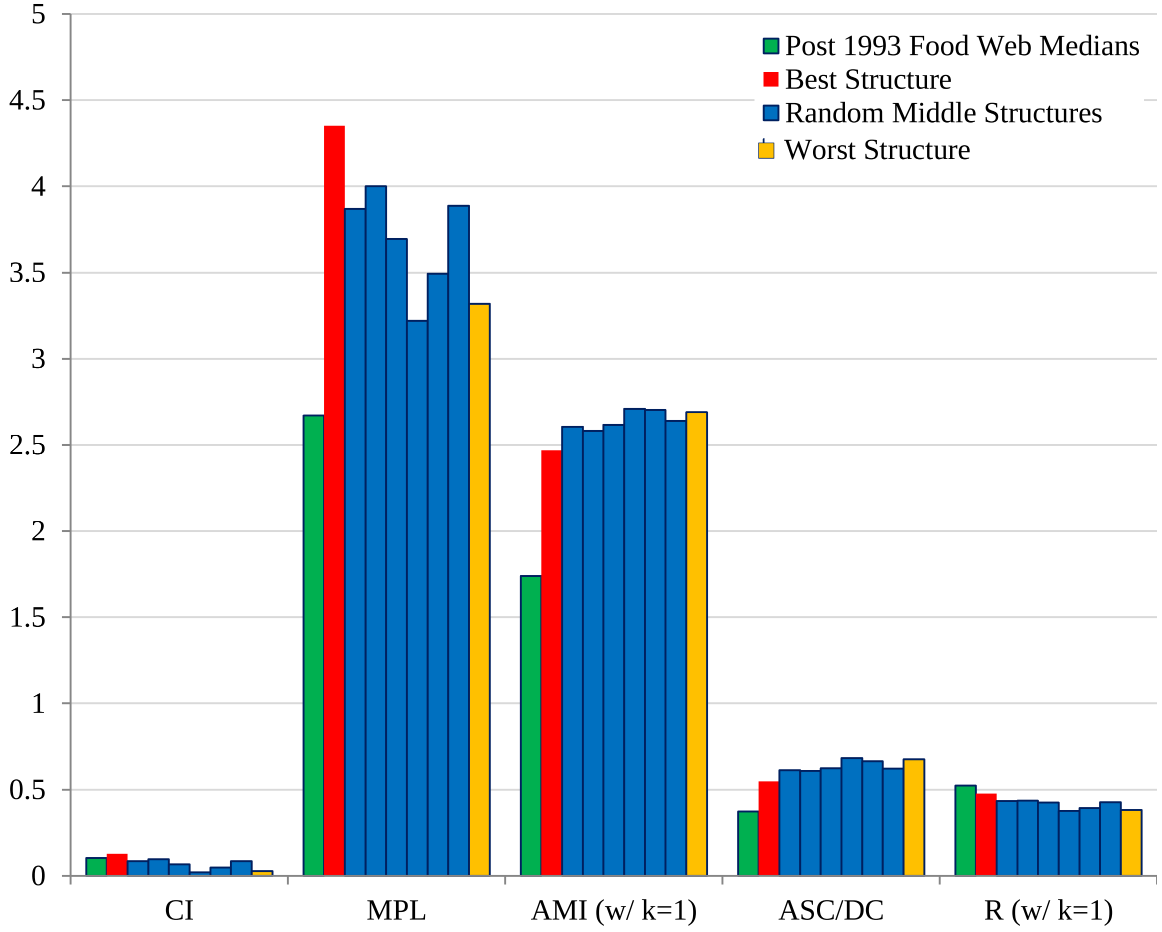


Figure 67: Non-dimensional flow metrics for optimizations of the best, worst and six random "middle" structural designs (as determined by the bio-inspired objective function based on the best combination of structural metrics: $G$, $P_S$, $P_R$, and $\lambda_{max}$ of the carpet recycling network.

The improvement of $Z_{trad}$ represents a reduction in cost and emissions, traditionally done through efficiency increases. An increase in efficiency, as discussed throughout chapter 8, generally requires a more highly constrained system. This value is measured by *AMI* and so we expect that a traditionally optimized network will have a high *AMI*. As seen in Figure 67, the bio-inspired optimization however results in a decrease in *AMI*. There is also a decrease in *DC*, reducing the ratio of the two (*ASC*/*DC*), a reflection of the strength of constraints on a system. Fewer constraints on the system mean more repetition and a higher robustness (*R*). An increase in *R* as the network is brought closer to food web medians is confirmed in Figure 67. This is an interesting result: when the network is traditionally optimized, i.e. optimizing directly for efficiency, robustness is decreased. When efficiency is increased indirectly, through designing the network to mimic food web metrics, robustness is increased. The metrics *AMI* and *R* both fall closer to food web medians for the carpet network designed using the bio-inspired structure than for the traditionally optimized network, which falls furthest from this structure.

Table 47 shows the design resulting from the original-traditional optimization is the furthest from the median food web values for *AMI*, *ASC*/*DC*, and *R*; this design actually closely matches the worst bio-inspired structure for all three metrics. This suggests that by maximizing the structural food web metrics, more opportunities are provided to the system than if resource usage is minimized as is standard in a traditional industry optimization.

Table 47: Non-dimensional flow-based food web metrics for the best and worst structures found using $G$, $P_S$, $P_R$, and $\lambda_{max}$ as compared to median food web values.

| | **Post 1993 Food Web Medians** | **Best Bio-Inspired Structure** | **Worst Bio-Inspired Structure** | **Traditional Optimization Result** |
|---|---|---|---|---|
| ***CI*** | 0.104 | 0.168 | 0.041 | 0.156 |
| ***MPL*** | 2.67 | 3.30 | 2.28 | 4.68 |
| ***AMI*** *(w/ k=1)* | 1.74 | 2.34 | 2.65 | 2.69 |
| ***ASC/DC*** | 0.372 | 0.477 | 0.590 | 0.591 |
| ***R*** *(w/ k=1)* | 0.523 | 0.510 | 0.449 | 0.449 |

The original analysis by Reap only used *CI* and *MPL*. For these two flow-based metrics the traditional optimization result produces very high values of both of these. Had the other flow metrics not been presented as options for a bio-inspired design analysis one might think that the traditional optimization result performs excellently in both the traditional and biological sense and see no reason to use a bio-inspired design approach. While *CI* and *MPL* provide valuable information about the behavior of the flows in the metric, they do not give a complete picture alone. This is a recurring theme among the food web metrics: an accurate depiction of a network requires multiple metrics.

Cycling index, a measure of the use of cyclic pathways, for the bio-inspired carpet network is slightly higher than for the worst bio-inspired network, very closely matching food web median values. Borrett and Salas found from a study of 50 ecosystems that cycling index fell between $0 \leq CI \leq 0.51$ (Borrett and Salas 2010). CI for the “best” carpet network here is 0.168, higher than the worst network but still on the low end of the range found for food webs. *MPL* describes a level of complexity in the flow or the level of participation of each actor in the path of a particular flow. The bio-inspired carpet network has a very high *MPL*, outperforming the median value for food webs and coming close to the highest value in the food web dataset.

Figure 68  plots system robustness, the relationship between the organizational constraints on the system and the level of redundancy in the system, for the best carpet network (best combination), the network optimized using only traditional methods, and the network designed using all 8 metrics, all 6 structural metrics, only *CI* and only *MPL*.  The post-1993 food webs are plotted as well and all reside at the peak of the robustness curve, following the hypothesis that ecological systems have mastered a balance between efficiency and redundancy to maximize their ability to survive system disturbances (Ulanowicz 2009). Were the carpet recycling network concerned with the threat of system perturbations of the same level and effect as food webs, then a bio-inspired network would benefit from a robustness that resided around the apex of this curve in the vicinity of that displayed by food webs.

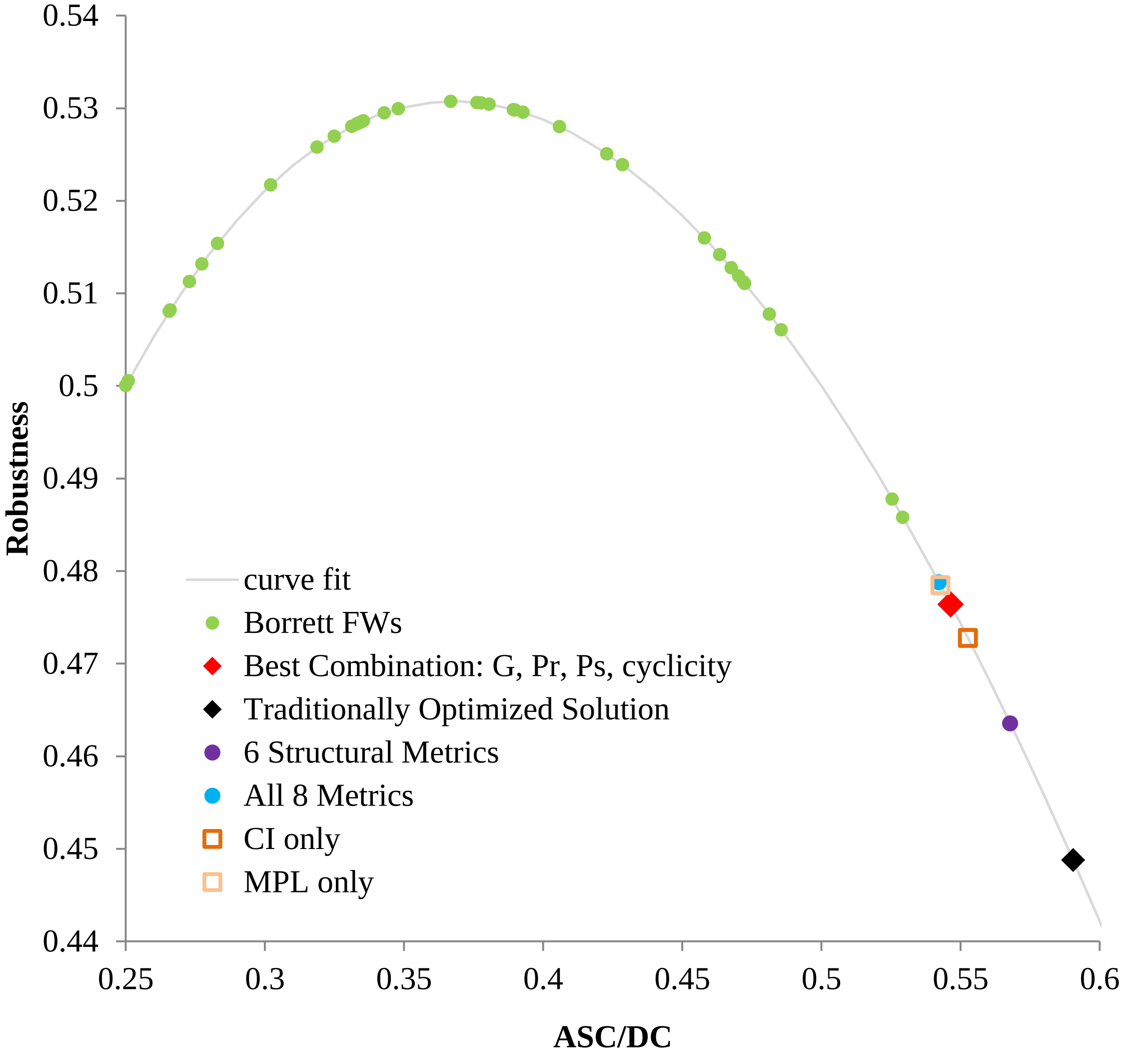


Figure 68: Robustness curve comparing the post 1993 food web dataset to the behavior of five different optimizations of the carpet recycling network. The five optimizations include the best combination ($G$, $P_R$, $P_S$, and $\lambda_{max}$), the traditionally optimized solution, all six structural metrics, all eight metrics from Reap's original investigation, only *CI*, and only *MPL*.

As seen for the highlighted industrial networks of section 8.5, the traditional optimization falls furthest to the right on the robustness curve in Figure 68. All of the carpet network configurations fall across a similar range as the water usage networks and the world zinc network (0.423-0.509). This is opposite however the hypothesis of Bodini and Bondavalli that human systems are characteristic of having large quantities of system imports that tend to be used inefficiently (Bodini and Bondavalli 2002). Both here and with the water and zinc networks earlier it is seen that the industrial networks are characteristic of higher efficiencies and less redundancy than food webs, making them more susceptible to negative effects caused by system disturbances. This in line however with the industry practice of keeping redundancy to a minimum to reduce system costs, resulting in a high dependence on imports.

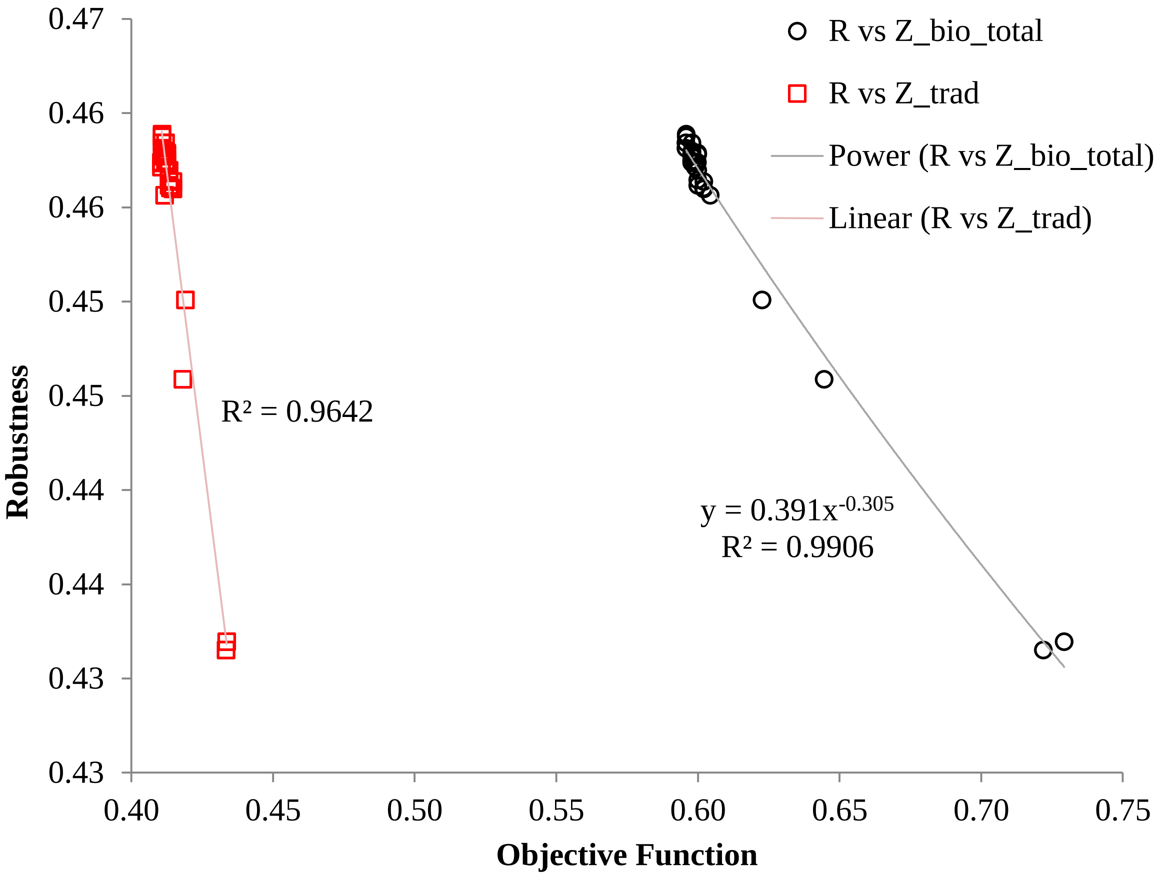


Figure 69: Changes in robustness plotted against changes in the objective function, both the overall bio-inspired function and the traditional objective function. The traditional objective function has a linear relationship with robustness and the bio-inspired objective function is shown to have a power relationship with robustness.

Changes in robustness with changes in the objective function, both the overall bio-inspired function and the traditional objective function, for all of the network scenarios where flow is held constant is shown in Figure 69. The scenarios plotted here are the scenarios of Figure 62 and Figure 63. The traditional objective function is seen to have a linear relationship with robustness. The correlation is very high showing an R2 value of 0.96 where increases in *Ztrad* result in decreases in robustness. The bio-inspired objective function is seen to have a power relationship with robustness, with decreases in robustness occurring at a slower rate than for the linear relationship with *Ztrad*.

The metric robustness stands out among the newly investigated flow metrics here. Figure 68 and Figure 69 both show that a network designed using food web metrics, specifically the four metrics $G$, $Ps$, $P_R$, and $\lambda_{max}$, will result in both a network optimized to reduce cost and emissions AND a network that has higher robustness than would be attained through meeting traditional design objectives alone.

## 9.8 Conclusions

Flow-information based food web metrics dominate network design; however the design of the underlying structure is still important. A two-step optimization procedure is proposed here using the four structural food web metrics ($G$, $Ps$, $P_R$, $\lambda_{max}$) to determine network structure and then followed by a traditional optimization of flow. The 'best' structure determined by these four metrics results in the 'best' carpet recycling network from both a traditional and a biological viewpoint. The structural step using these four metrics has an $R^2$ value of 0.87 with minimizations of the traditional objective function. The four metrics highlighted together monitor the presence and strength of cycling in the system and the levels of specialized vs general actors, covering both structure and function.

The metric robustness stands out among the newly investigated flow metrics for its potential use as a flow design metric in addition to mean path length and cycling index. Robustness is already an important behavior in industry networks where system perturbations can cause losses in profits, jobs, and the distribution of necessary materials and energy. The study of robustness changes due to design changes in thermodynamic networks shows that there seems to be certain design configurations that manage to increase efficiency without decreasing robustness.

# CHAPTER 10

# SUMMARY AND FUTURE WORK

## 10.1 Summary

The successful implementation of closed-loop industrial networks will make economic growth possible while simultaneously safeguarding the environment, both of which are necessary to meet the demands of a rapidly growing population. Increased production, with more efficient and sustainable industrial processes, coupled with the complete reuse of byproducts is necessary for these goals to be met. Food webs are efficient, sustainable, and low impact, all of which is characterized by their closed-loop structure. It is this structure that we would like to emulate in industry to meet these goals.

Design guidelines are made here with regards to the use of different food web analysis techniques. The use of a food web matrix [**F**] for EIP-FW analyses and comparisons is proposed here, as using a community matrix [**C**] may not be appropriate. As described in the *Ecosystem Network Analysis* section, the community matrix documents all interactions as bi-directional, double counting each interaction and further increasing the number of linkages documented. The community matrix also includes competitive interactions between species. From a material and energy flow perspective, only a direct relationship (who eats whom) seems relevant in industry. Including competition in ecological matrices originally was used to measure the complexity of interactions and not provide insights into material flow. Moreover most industry interactions are specific, so that even if companies A and B both receive flow from company C, they will receive flows of different substance/quality and therefore not be in competition with each other. This makes it more difficult to analogize competition into an EIP setting. Computations should include the potential for cannibalism however. This is in response to the ecological significance of this interaction and the reasonable ability for it to occur amongst industrial actors. Thus it is also advised here that all future comparisons of the metric connectance be calculated from the equation that accounts for the possibility of cannibalistic interactions (equation 10) rather than the alternate scenario that does not allow for this possibility (equation 11).

Due to the nature of the changes made in the early 90’s to the collection and documentation of food webs, and the strong impact on the types of interactions represented and effect on common metrics, we propose that the food web dataset ‘*FWPost*’ be used for EIP comparisons. The food webs in this collection are a much more accurate representation of the ecological networks and how the species in such a network interact. They are much larger networks with higher diversity and a higher density of linkages. They also show a significantly more complex cycling structure than those food webs which were collected prior to 1993. By focusing on only those food webs which were collected after 1993, EIP designers need worry less about how representative the food web data actually is. Documentation techniques imposed in the early 90’s have resulted in webs that are more structurally complete by assuring they document all potential functional roles and feeding relationships in a uniform manner. Although using this dataset, as opposed to the compilation of pre-1993 and post-1993, gives an even higher benchmark for EIP design to reach for, it will provide more realistic appraisal, and hopefully allow for richer insights into how to design more sustainable industrial systems.

Further design guidelines are presented here in the form of four structural-information based food web metrics: generalization, cyclicity, specialized predator fraction, and prey to predator ratio, used in a two-step optimization procedure. The obvious biological characteristics we wish to mimic, such as sustainability, recycling and reuse, and efficiency are all controlled by the behavior of these metrics. With the help of these metrics and the use of goal values from a set of food webs, suggested here to be only made up of those collected after the early 90’s, the design of industrial resource networks changes from a cost minimization driven problem to a much more thoughtful and complex challenge. The problem with an optimization based solely on cost is that a sustainable network needs much more than low profit margins to survive. Network behaviors are all linked to the overall form of the network. Behaviors may be things such as response times in the face of system disturbances, the efficiency that imported materials and energy are used, and the amounts of externally imported materials and energy needed. Network form consists of the presence and complexity of cycling present in the structure, relative numbers of actors in the system that interact exclusively with another or inclusively with a large part of the network, and the number of actors any material or energy stream will visit before it exits the system. Food web metrics exist that quantify the behavior of these properties and more.

This work establishes decisively that the conventional wisdom, that biologically inspired network design looks like "waste equals food" and linear food chains, is a poor representation of the wealth of design knowledge available from ecosystems. The food web metric cyclicity embodies the web like structure and cycling of ecosystems, which is a far cry from a linear chain. Functional relationships in a network, represented by cannibalistic behavior, omnivory, detritus, and specialization amongst participating species, all contribute to the presence of cycling in the network. The maximization of cyclicity alone is not enough to ensure success for an EIP however, as both industrial networks with higher and low cyclicity (high cyclicity being characteristic of food webs) have failed. This is the benefit of the combination of 4 metrics found; the coupling of cyclicity with metrics that influence the functional relationships in the system bring industrial networks closer to the desired results. The maximization of cyclicity and the inclusion of system actors that mimic the basic functions represented in food webs contribute to the achievement of the innate efficiency, sustainability, and robustness of ecosystems.

Current industrial networks that aim to mimic nature are found to fall short of their goal. 48 eco-industrial parks are collected and analyzed here using structural food web metrics, the first food web analysis of eco-industrial parks of this scale. Following the importance of cyclicity in establishing the groundwork for an analogous food web type structure in industry, the eco-industrial parks collected are organized following the level of cycling present in the system. None of the systems, despite their status, successfully match the average values found for biological ecosystems. The results show clearly what a few previous studies suggested, that even those networks with the best intentions still do not come close to the structure of food webs.

Robustness among other flow based metrics might be a productive path forward in the bio-inspired design of industrial resource networks. The approach is shown here to have a real and significant value to industry. Robustness and cyclicity are both investigated using thermodynamic power cycles, addressing a common fault of bio-inspired design in its prolific use of qualitative reasoning. This gap in the field is remedied by elucidating a positive relationship between two key design metrics (cyclicity and robustness) and 1st law -or- thermodynamic efficiency, creating a heretofore unrecognized relationship between the two. Cyclicity is shown to quantitatively correlate to increases in efficiency. The investigation of robustness results in a quantitative connection between efficiency and redundancy: in general efficiency increases are shown to reduce system robustness however increase in efficiency and repetition are not mutually exclusive results. This shows that, in contrast to the harsh critiques of the use of bio-inspired designs, there is in fact 1st principle-based evidence of the success of this method, and these metrics in particular.

Additionally, the beneficial side effects of mimicking food web properties in industrial networks are still being discovered. An example of such a property is a system’s ability to sustain very specialized industries. More work is still needed in order to quantify these larger systemic benefits which are characteristic of nature and its ecosystems. With continued progress we may be able to successfully transfer these properties, among others, to both newly developing and long standing industrial networks.

## 10.2 Future Work

The work done in this dissertation sets the stage for numerous potential research questions regarding the how best properties unique to industrial networks can be represented in a food web analogy. Many of the areas of interest depend on the ability of researchers to have access to more detailed information for the EIPs being investigated. There are also many more food web metrics that should be investigated for their potential to aid in the successful design of industrial networks.

## Future Application of Ecosystem Network Analysis for EIPs

The industrial properties that have been translated into the vocabulary of food webs here, and vice versa, present more questions about the importance of additional properties that have not yet been investigated, the definition of sustainability, failure, and extinction all present interesting and important research questions. There is currently no cohesive measure for industrial networks as to how to measure sustainability. What is a measure of sustainability for these parks? Must we look at money, environmental impact, relative distances? Sustainability can also be related to failure or species extinction. This however proposes the questions: What does it mean for an EIP to fail and how can this be quantified? What are causes of EIP failures or collapse? How do we define species extinction in industry? Extinction and failure both present the dimension of time that was neglected here in assuming all networks to be operating at steady state. This presents a different problem from the steady state EIPs and food webs used here. The process of structures passing out of operation in EIPs occurs on a temporal time frame. The timeline of EIPs are much shorter than the timelines of food webs and therefore this may not be an appropriate assumption. How can time in an industry sense be dealt with in an analogy with food webs?

Agriculture was investigated only very preliminarily here, but presents an interesting area of exploration if more detailed information for EIPs can be collected. As agriculture forms its own food web, does having a real food web as a component of an industrial ecosystem bring the entire system closer to a sustainable biological state? If this is the case then does agriculture become a necessary component of an eco-industrial park in order to successfully mimic food web behavior?

The food web property of using an aggregate definition of species was found here to be a fundamental difference in the basic definition of an actor between the biological and industrial networks. When each company is a species (the analogy as currently used) a population of one is created for each species. Population effects within each species in a food web average out fluctuations in individuals. The effects and possible benefits of large population sizes for each species have not been translated to EIPs. What is known following the work here is that the aggregation of actors in an EIP does have an effect on the results of a food web analysis, and so methods of aggregation for industrial networks are worthy of investigation. This is important with the growing prevalence of world markets, for example the expansive network world zinc network of section 8.6.3. Species aggregation may be found to only make sense for large networks such as the world zinc network.

### Expanding the Dataset of EIPs

The future questions posed above regarding temporal and population size effects both need an expansion of the EIP dataset beyond the already expanded version provided here. Continuing the collection of EIPs, especially those with greater than 30 companies, would give further insight to all analyses done in this dissertation and proposed as future work. The further investigation of the indirect effects presented in this work also needs an expanded dataset.

Indirect effects in food webs are a current ecological research area that is turning out to be extremely interesting in the relation to diversity and cyclicity. The investigation here of indirect effects in industrial networks provides an easy transition for the study of indirect effects in eco-industrial parks. Understanding the importance of these background relationships holds serious potential for the establishment of additional design relationships.

Studying indirect effects further than what was done here requires flow-information to be known for the network. Expanding the EIP dataset to include flow information, such as magnitude and environmental importance, would allow for the use of additional food web metrics give a more balanced summary of the network. Flow-based information is currently exceedingly difficult to obtain and often proprietary, with the currently available sources severely limited. This is hopefully an issue which will be resolved as the successes and positive impacts, both environmentally and financially, of designing industrial networks to mimic food webs become more obvious. This goal is promoted here through the presentation of the valuable information that can be gained from the use of flow metrics. The hope is that industry will be swayed by this new knowledge field and to aid researchers by providing flow information, enabling a continuation of new developments and future work in this area.

### Generation of a Hypothetical Industrial Network Model

The proposed two-step optimization procedure for the design of bio-inspired industry networks here would be further supported by testing on a basic-hypothetical model of an industrial network. Such a model would be very interesting and the analyses stemming from the generation of multiple such models for additional testing of the conclusions drawn in this work would be very rich. Specifically the model could provide a host of additional analyses, including expansions on the best combination of structural metrics found here, the related two-step optimization procedure, and the initial findings on the flow based metrics presented.

### Further Quantitative Analyses

Maximization of system work, the property measured by thermodynamic efficiency, becomes an important goal when aiming to base closed-loop industrial systems on ecological ones. One may ask, what is the definition of system work in an ecosystem? What is the analogy between the average heat input temperature of a thermodynamic power cycle and measurable quantities in an ecosystem? Although answering these answers may or may not yield better system designs, it is doubtful that one would ask the questions were it not for the investigation between thermal efficiency and the metrics cyclicity and robustness. Alternate power cycle models should be analyzed to further validate the positive relationship between cyclicity and maximum thermal efficiency and further investigate the relationship between efficiency and robustness. Other analyses will most likely continue to show the importance of cyclical connections to the efficient use and production of energy and matter. Additional cycles beyond thermodynamic and industrial should be investigated to broaden the positive relationship seen here to one between any network structure and its efficiency.

## 10.3 In Closing

This dissertation proposes the use of biological food webs as a source for cost reduction, efficiency improvements, and environmental burden reduction in industrial resource networks. The approach proposed here mimics the structure of food webs using key quantities as determined by ecologists. These quantities include such things as system connectivity and interaction density. This thesis uses a comprehensive and reliable dataset and quantitative engineering analyses to meet the proposed objectives. The feasibility of this work has been demonstrated through both preliminary results and previous research. A growing number of publications analyzing EIPs indicate a renewed interest in the area (Ehrenfeld and Gertler 1997, Chertow 2000, Chertow 2007, van Beers, Corder et al. 2007, van Berkel 2009). Reap observed that a carpet recycling network designed using biologically inspired metrics correlated to a financially superior recycling network (Reap 2009). Layton et al. observed that thermodynamic power cycles optimized using the standard 1st Law efficiency correlated to a high degree with increases in cyclicity, a metric used by ecologists to measure the internal cycling of materials and energy in food webs (Layton, Reap et al. 2012). These analyses among others, warrant the application of other ecological measures and metrics. Using ecological network patterns embodying both economically and environmentally desirable properties, biologically redesigned industrial networks can ease both environmental and economic burdens.

# APPENDIX A

## THERMODYNAMIC POWER CYCLES: MATRICES AND DATA

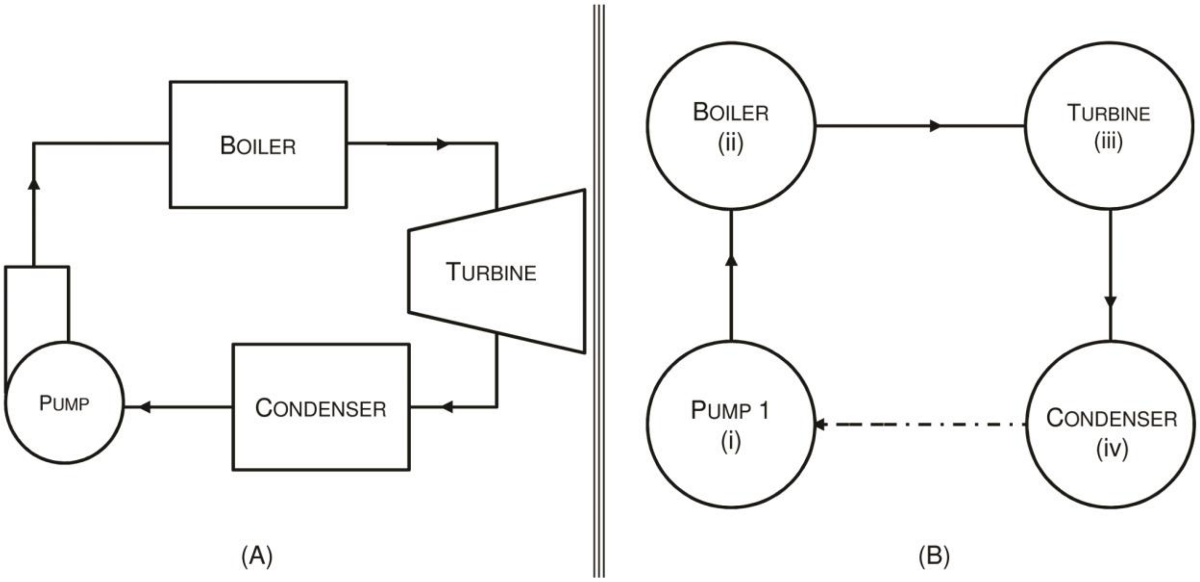


Figure A70: Basic Rankine cycle idealized equipment diagram for a power cycle (a), energy flow diagram (b).

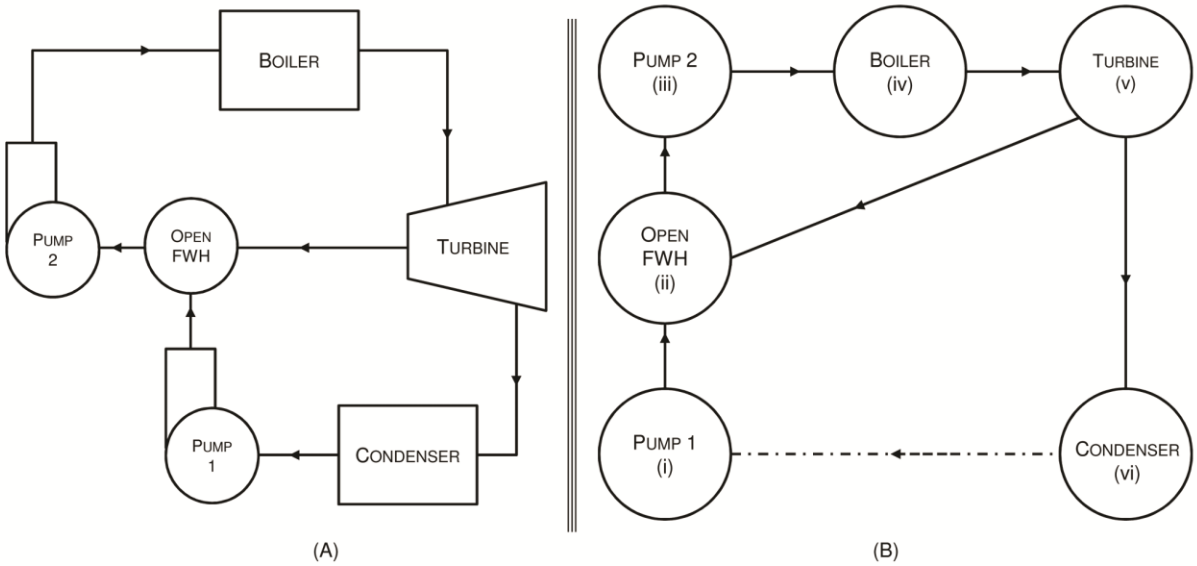


Figure A71: Rankine cycle with one open feed water heater idealized equipment diagram for a power cycle (a), energy flow diagram (b).

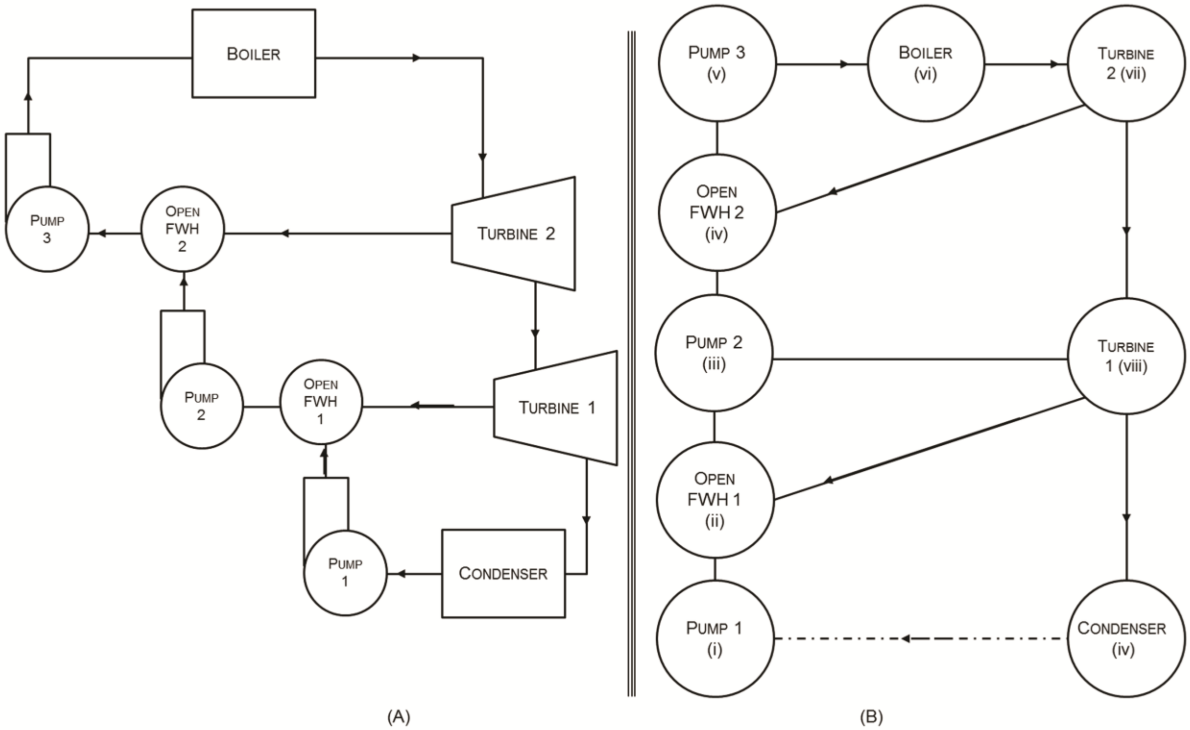


Figure A72: Rankine cycle with two open feed water heaters idealized equipment diagram for a power cycle (a), energy flow diagram (b).

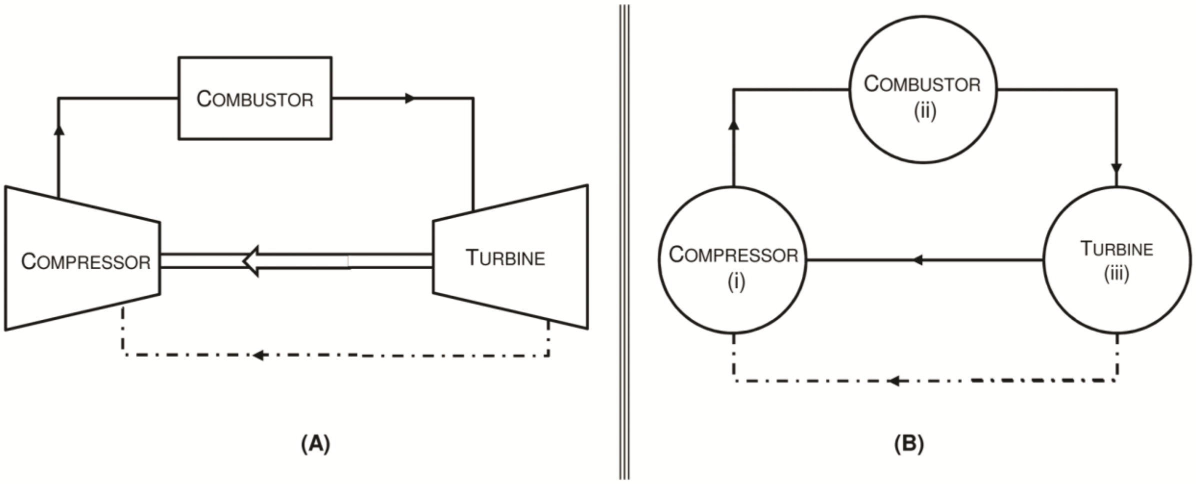


Figure A73: Basic Brayton cycle idealized equipment diagram for a power cycle (a), energy flow diagram (b).

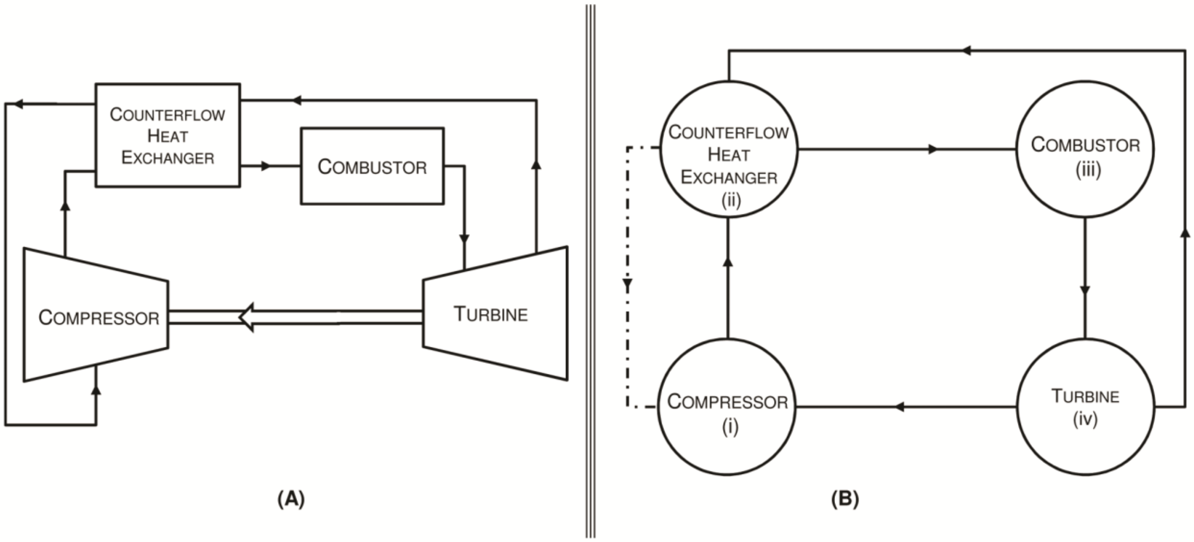


Figure A74: Brayton cycle with regeneration (i.e. counterflow heat exchanger) idealized equipment diagram for a power cycle (a), energy flow diagram (b).

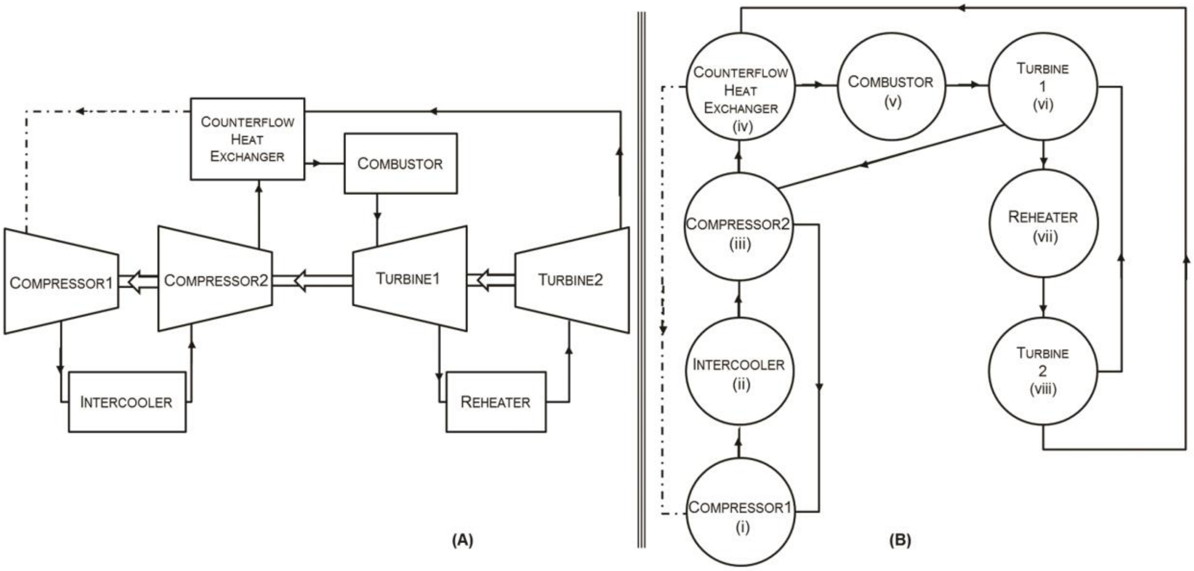


Figure A75: Brayton cycle with regeneration (i.e. counterflow heat exchanger), intercooling, and reheat (2 turbines) idealized equipment diagram for a power cycle (a), energy flow diagram (b).

Table A48: Flow metric results for five Brayton cycle configurations. Cycle labels follow the labels used in chapter 4: (B1) – basic Brayton, (B2) – Brayton with regeneration, (B3) – Brayton with regeneration, intercooling, and reheat (2 turbines), (B4) - with regeneration, intercooling, and reheat (3 turbines), (B5) - with regeneration, intercooling, and reheat (4 turbines). A constant multiplier *k* equal to one was used for *AMI*.

| | **(B1)** | **(B2)** | **(B3)** | **(B4)** | **(B5)** |
|---|---|---|---|---|---|
| **CI** | *0.197* | *0.380* | *0.435* | *0.454* | *0.466* |
| **MPL** | *3.00* | *4.92* | *8.14* | *11.4* | *14.6* |
| **AMI** | *1.50* | *1.51* | *2.37* | *2.87* | *3.27* |
| **TSTp** ($x10^4$) | *0.482* | *0.550* | *0.905* | *1.31* | *1.68* |
| **ASC** ($x10^4$) | *0.722* | *0.831* | *2.15* | *3.77* | *5.51* |
| **DC** ($x10^4$) | *1.11* | *1.65* | *3.31* | *5.43* | *7.49* |
| **TSO** ($x10^4$) | *0.389* | *0.817* | *1.17* | *1.67* | *1.99* |
| **ASC/DC** | *0.650* | *0.504* | *0.648* | *0.69* | *0.735* |
| **R** | *0.404* | *0.498* | *0.406* | *0.366* | *0.327* |
| $\lambda_{max}$ | *1* | *1.22* | *1.36* | *1.43* | *1.47* |
| $\eta_{th}$ | *0.482* | *0.563* | *0.685* | *0.718* | *0.733* |

Table A49: Flow metric results for nine Rankine cycle configurations. Cycle labels follow the labeling used in chapter 4: (R1) - basic Rankine, (R5) – Rankine with 1 open feedwater heater (FWH), (R6) – Rankine with 2 open FWHs, (R8) – Rankine with 3 open FWHs, (R10) – Rankine with 4 open FWHs, (R11) – Rankine with 5 open FWHs, (R12) – Rankine with 6 open FWHs, (R13) – Rankine with 7 open FWHs, (R14) – Rankine with 8 open FWHs.  A constant multiplier k equal to one was used for AMI.

| | **(R1)** | **(R5)** | **(R6)** | **(R8)** | **(R10)** | **(R11)** | **(R12)** | **(R13)** | **(R14)** |
|---|---|---|---|---|---|---|---|---|---|
| **CI** | *0* | *0.181* | *0.188* | *0.190* | *0.190* | *0.186* | *0.178* | *0.168* | *0.186* |
| **MPL** | *2.65* | *3.54* | *4.47* | *4.80* | *5.15* | *5.47* | *7.69* | *5.05* | *6.58* |
| **AMI** | *1.70* | *1.93* | *2.18* | *2.37* | *2.57* | *2.76* | *2.44* | *2.93* | *3.26* |
| **TST** ($x10^4$) | *1.31* | *1.35* | *1.63* | *1.72* | *1.65* | *1.73* | *2.33* | *1.73* | *2.03* |
| **ASC** ($x10^4$) | *2.22* | *2.60* | *3.56* | *4.07* | *4.24* | *4.79* | *5.70* | *5.07* | *6.63* |
| **DC** ($x10^4$) | *3.15* | *3.88* | *5.13* | *5.77* | *5.92* | *6.53* | *9.20* | *7.07* | *8.53* |
| **TSO** ($x10^4$) | *0.927* | *1.28* | *1.57* | *1.70* | *1.68* | *1.74* | *3.51* | *2.01* | *1.90* |
| **ASC/DC** | *0.706* | *0.670* | *0.693* | *0.706* | *0.716* | *0.733* | *0.619* | *0.716* | *0.78* |
| **R** | *0.355* | *0.387* | *0.366* | *0.355* | *0.345* | *0.328* | *0.428* | *0.345* | *0.283* |
| $\lambda_{max}$ | *0* | *1* | *1.15* | *1.21* | *1.24* | *1.25* | *1.45* | *1.27* | *1.27* |
| $\eta_{th}$ | *0.430* | *0.463* | *0.472* | *0.476* | *0.479* | *0.48* | *0.482* | *0.482* | *0.483* |

# APPENDIX B

## FOOD WEBS: INFORMATION AND DATA

Table B50: Food Webs collected by Borrett and Lau (Borrett and Lau 2013) and used in this dissertation. The original references for the 58 food webs may be found in (Borrett and Lau 2013).

| | **Name** | **Original Reference** *as listed in (Borrett and Lau 2013)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| **1** | Marine Coprophagy (oyster) | *Haven and Morales-Alamo (1966)* | Pre | N |
| **2** | Lake Findley | *Richey et al. (1978)* | Pre | N |
| **3** | Mirror Lake | *Richey et al. (1978)* | Pre | N |
| **4** | Lake Wingra | *Richey et al. (1978)* | Pre | N |
| **5** | Marion Lake | *Richey et al. (1978)* | Pre | N |
| **6** | Cone Springs | *Tilly (1968)* | Pre | Y |
| **7** | Silver Springs | *Odum (1957)* | Pre | Y |
| **8** | English Channel | *Brylinsky (1972)* | Pre | N |
| **9** | Oyster Reef | *Dame and Patten (1981)* | Pre | Y |
| **10** | Baie de Somme | *Rybarczyk et al. (2003)* | Pre | N |
| **11** | Bothnian Bay | *Sandberg et al. (2000)* | Post | N |
| **12** | Bothnian Sea | *Sandberg et al. (2000)* | Post | N |
| **13** | Ythan Estuary | *Baird and Milne (1981)* | Pre | N |
| **14** | Sundarban Mangrove (virgin) | *Ray (2008)* | Post | Y |
| **15** | Sundarban Mangrove (reclaimed) | *Ray (2008)* | Post | Y |
| **16** | Baltic Sea | *Baird et al. (1991)* | Pre | N |
| **17** | Ems Estuary | *Baird et al. (1991)* | Pre | N |
| **18** | Swartkops Estuary 15 | *Baird et al. (1991)* | Pre | N |
| **19** | Southern Benguela Upwelling | *Baird et al. (1991)* | Pre | N |
| **20** | Peruvian Upwelling | *Baird et al. (1991)* | Pre | N |
| **21** | Crystal River (control) | *Ulanowicz (1986)* | Pre | Y |
| **22** | Crystal River (thermal) | *Ulanowicz (1986)* | Pre | Y |

Table B50 continued: Food Webs collected by Borrett and Lau (Borrett and Lau 2013) and used in this dissertation. The original references for the 58 food webs may be found in (Borrett and Lau 2013).

| | **Name** | **Original Reference** *as listed in (Borrett and Lau 2013)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| **23** | Charca de Maspalomas Lagoon | *Almunia et al. (1999)* | Pre | N |
| **24** | Northern Benguela Upwelling | *Heymans and Baird (2000)* | Post | N |
| **25** | Swartkops Estuary | *Scharler and Baird (2005)* | Post | Y |
| **26** | Sunday Estuary | *Scharler and Baird (2005)* | Post | Y |
| **27** | Kromme Estuary | *Scharler and Baird (2005)* | Post | Y |
| **28** | Okefenokee Swamp | *Whipple and Patten (1993)* | Post | Y |
| **29** | Neuse Estuary (early summer 1997) | *Baird et al. (2004b)* | Post | N |
| **30** | Neuse Estuary (late summer 1997) | *Baird et al. (2004b)* | Post | N |
| **31** | Neuse Estuary (early summer 1998) | *Baird et al. (2004b)* | Post | N |
| **32** | Neuse Estuary (late summer 1998) | *Baird et al. (2004b)* | Post | N |
| **33** | Gulf of Maine | *Link et al. (2008)* | Post | Y |
| **34** | Georges Bank | *Link et al. (2008)* | Post | Y |
| **35** | Middle Atlantic Bight | *Link et al. (2008)* | Post | Y |
| **36** | Narragansett Bay | *Monaco and Ulanowicz (1997)* | Post | Y |
| **37** | Southern New England Bight | *Link et al. (2008)* | Post | Y |
| **38** | Chesapeake Bay | *Baird and Ulanowicz (1989)* | Pre | N |
| **39** | Mondego Estuary (Zostera sp. Meadows) | *Patricio and Marques (2006)* | Post | Y |
| **40** | St. Marks Seagrass, site 1 (Jan.) | *Baird et al. (1998)* | Post | Y |
| **41** | St. Marks Seagrass, site 1 (Feb.) | *Baird et al. (1998)* | Post | Y |
| **42** | St. Marks Seagrass, site 2 (Jan.) | *Baird et al. (1998)* | Post | Y |
| **43** | St. Marks Seagrass, site 2 (Feb.) | *Baird et al. (1998)* | Post | Y |

Table B50 continued: Food Webs collected by Borrett and Lau (Borrett and Lau 2013) and used in this dissertation. The original references for the 58 food webs may be found in (Borrett and Lau 2013).

| | **Name** | **Original Reference** *as listed in (Borrett and Lau 2013)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| **44** | St. Marks Seagrass, site 3 (Jan.) | *Baird et al. (1998)* | Post | Y |
| **45** | St. Marks Seagrass, site 4 (Feb.) | *Baird et al. (1998)* | Post | Y |
| **46** | Sylt-RomoBight | *Baird et al. (2004a)* | Post | N |
| **47** | Graminoids (wet) | *Ulanowicz et al. (2000)* | Post | Y |
| **48** | Graminoids (dry) | *Ulanowicz et al. (2000)* | Post | Y |
| **49** | Cypress (wet) | *Ulanowicz et al. (1997)* | Post | Y |
| **50** | Cypress (dry) | *Ulanowicz et al. (1997)* | Post | Y |
| **51** | Lake Oneida (pre-ZM) | *Miehls et al. (2009a)* | Post | Y |
| **52** | Lake Oneida (post-ZM) | *Miehls et al. (2009a)* | Post | Y |
| **53** | Bay of Quinte (pre-ZM) | *Miehls et al. (2009b)* | Post | Y |
| **54** | Bay of Quinte (post-ZM) | *Miehls et al. (2009b)* | Post | Y |
| **55** | Mangroves (wet) | *Ulanowicz et al. (1999)* | Post | N |
| **56** | Mangroves (dry) | *Ulanowicz et al. (1999)* | Post | N |
| **57** | Florida Bay (wet) | *Ulanowicz et al. (1999)* | Post | Y |
| **58** | Florida Bay (dry) | *Ulanowicz et al. (1999)* | Post | Y |

Table B51: Food Web data as collected by Dunne and used in this dissertation. The original references for the 17 food webs may be found in (Borrett, Fath et al. 2007).

| | **Name** | **Original Reference** *as listed in (Borrett, Fath et al. 2007)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| **1** | Coachella Valley | *Polis 1991* | pre | Y |
| **2** | St. Martin Island | *Goldwasser and Roughgarden 1993* | post | Y |
| **3** | El Verde Rainforest | *Waide and Reagan 1996* | post | Y |
| **4** | UK Grassland | *Martinez et al. 1999* | post | N |
| **5** | Scotch Broom | *Memmott et al. 2000* | post | N |
| **6** | Skipworth Pond | *Warren 1989* | pre | Y |
| **7** | Bridge Brook Lake | *Havens 1992* | pre | Y |
| **8** | Little Rock Lake | *Martinez et al. 1999* | post | N |
| **9** | Canton Creek | *Townsend et al. 1998* | post | Y |
| **10** | Stony Stream | *Townsend et al. 1998* | post | Y |
| **11** | Chesapeake Bay | *Baird and Ulanowicz 1989* | pre | N |
| **12** | St. Marks Estuary | *Christian and Luczkovich 1999* | post | Y |
| **13** | Ythan Estuary 1991 | *Hall and Raffaelli 1991* | pre | N |
| **14** | Ythan Estuary 1996 | *Huxham et al. 1996* | post | N |
| **15** | Benguela | *Yodzis 1998* | post | N |
| **16** | Caribbean Reef Small | *Opitz 1996* | post | Y |
| **17** | NE US Shelf | *Link 2002* | post | Y |

Table B52: Food Web data as collected by Briand and Cohen and used in this dissertation (Briand 1983, Briand and Cohen 1987). The original references for the 69 food webs may be found in (Briand 1983, Briand and Cohen 1987).

| | **Name** *(M = modified to include detritus links)* | **Original Reference** *as listed in (Briand 1983)and (Briand and Cohen 1987)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| ***1*** | Cochin Estuary | *Qazim (1970)* | Pre | N |
| ***2*** | Cochin Estuary (M) | *Qazim (1970)* | Pre | Y |
| ***3*** | Knysna Estuary | *Day (1967)* | Pre | N |
| ***4*** | Knysna Estuary (M) | *Day (1967)* | Pre | Y |
| ***5*** | Long Island Salt Marsh | *Woodwell (1967)* | Pre | N |
| ***6*** | Long Island Salt Marsh (M) | *Woodwell (1967)* | Pre | Y |
| ***7*** | California Salt Marsh | *Johnston (1956)* | Pre | N |
| ***8*** | Georgia Salt Marsh | *Teal (1962)* | Pre | N |
| ***9*** | California Tidal Flat | *MacGinitie (1935)* | Pre | N |
| ***10*** | California Tidal Flat (M) | *MacGinitie (1935)* | Pre | Y |
| ***11*** | Narragansett Bay | *Kremer and Nixon (1978)* | Pre | N |
| ***12*** | Narragansett Bay (M) | *Kremer and Nixon (1978)* | Pre | Y |
| ***13*** | Bissel Cove Salt Marsh | *Nixon and Oviatt (1973)* | Pre | N |
| ***14*** | Bissel Cove Salt Marsh (M) | *Nixon and Oviatt (1973)* | Pre | Y |
| ***15*** | Lough Ine Rapids | *Kitching and Ebling (1967)* | Pre | N |
| ***16*** | Exposed Rocky Shore-New England | *Menge and Sutherland (1976)* | Pre | N |
| ***17*** | Exposed Rocky Shore-New England (M) | *Menge and Sutherland (1976)* | Pre | Y |
| ***18*** | Mangrove Swamp-Station 1 | *Menge and Sutherland (1976)* | Pre | N |
| ***19*** | Mangrove Swamp-Station 1 (M) | *Menge and Sutherland (1976)* | Pre | Y |
| ***20*** | Protected Rocky Shore-New England | *Menge and Sutherland (1976)* | Pre | N |
| ***21*** | Protected Rocky Shore-New England (M) | *Menge and Sutherland (1976)* | Pre | Y |
| ***22*** | Mangrove Swamp-Station 3 | *Menge and Sutherland (1976)* | Pre | N |

Table B52 continued: Food Web data as collected by Briand and Cohen and used in this dissertation (Briand 1983, Briand and Cohen 1987). The original references for the 69 food webs may be found in (Briand 1983, Briand and Cohen 1987).

| | **Name** *(M = modified to include detritus links)* | **Original Reference** *as listed in (Briand 1983)and (Briand and Cohen 1987)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| ***23*** | Mangrove Swamp-Station 3 (M) | *Menge and Sutherland (1976)* | Pre | Y |
| ***24*** | Exposed Rocky Shore-Washington | *Walsh (1967)* | Pre | N |
| ***25*** | Exposed Rocky Shore-Washington (M) | *Walsh (1967)* | Pre | Y |
| ***26*** | Pamlico River | *Walsh (1967)* | Pre | N |
| ***27*** | Pamlico River (M) | *Walsh (1967)* | Pre | Y |
| ***28*** | Protected Rocky Shore-Washington | *Copeland et. al. (1974)* | Pre | N |
| ***29*** | Protected Rocky Shore-Washington (M) | *Copeland et. al. (1974)* | Pre | Y |
| ***30*** | Coral Reefs | *Hiatt and Strasburg (1960)* | Pre | N |
| ***31*** | Coral Reefs with detritus | *Hiatt and Strasburg (1960)* | Pre | Y |
| ***32*** | Kapingamarangi Atoll | *Niering (1963)* | Pre | N |
| ***33*** | Moosehead Lake | *Brooks and Deevey (1963)* | Pre | N |
| ***34*** | Antarctic Pack Ice Zone | *Knox (1970)* | Pre | N |
| ***35*** | Antarctic Pack Ice Zone (M) | *Knox (1970)* | Pre | Y |
| ***36*** | Ross Sea | *Patten and Finn (1979)* | Pre | N |
| ***37*** | Ross Sea with detritus | *Patten and Finn (1979)* | Pre | Y |
| ***38*** | Bear Island | *Summerhayes and Elton (1923)* | Pre | N |
| ***39*** | Canadian Prairie | *Bird (1930)* | Pre | N |
| ***40*** | Canadian Willow Forest | *Bird (1930)* | Pre | N |
| ***41*** | Aspen Parkland | *Bird (1930)* | Pre | N |
| ***42*** | Canadian Aspen Forest Communities | *Bird (1930)* | Pre | N |
| ***43*** | Wytham Wood | *Varley (1970)* | Pre | N |
| ***44*** | New Zealand Salt Meadow | *Paviour-Smith (1956)* | Pre | N |

Table B52 continued: Food Web data as collected by Briand and Cohen and used in this dissertation (Briand 1983, Briand and Cohen 1987). The original references for the 69 food webs may be found in (Briand 1983, Briand and Cohen 1987).

| | **Name** *(M = modified to include detritus links)* | **Original Reference** *as listed in (Briand 1983)and (Briand and Cohen 1987)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| ***45*** | Arctic Seas | *Dunbar (1954)* | Pre | N |
| ***46*** | Arctic Seas (M) | *Dunbar (1954)* | Pre | Y |
| ***47*** | Antarctic Seas | *Mackintosh (1964)* | Pre | N |
| ***48*** | Black Sea epiplankton | *Petipa et al. (1970)* | Pre | N |
| ***49*** | Black Sea epiplankton (M) | *Petipa et al. (1970)* | Pre | Y |
| ***50*** | Black Sea bathyplankton | *Petipa et al. (1970)* | Pre | N |
| ***51*** | Black Sea bathyplankton (M) | *Petipa et al. (1970)* | Pre | Y |
| ***52*** | Crocodile Creek | *Fryer (1959)* | Pre | N |
| ***53*** | River Clydach | *Jones (1949)* | Pre | N |
| ***54*** | River Clydach (M) | *Jones (1949)* | Pre | Y |
| ***55*** | Morgan's Creek | *Minshall (1967)* | Pre | N |
| ***56*** | Morgan's Creek (M) | *Minshall (1967)* | Pre | Y |
| ***57*** | Mangrove Swamp-Station 6 | *Walsh (1967)* | Pre | N |
| ***58*** | Mangrove Swamp-Station 6 (M) | *Walsh (1967)* | Pre | Y |
| ***59*** | Marine Sublittoral | *Clarke et al. (1967)* | Pre | N |
| ***60*** | Lake Nyasa Rocky Shore | *Fryer (1959)* | Pre | N |
| ***61*** | Lake Nyasa Sandy Shore (M) | *Fryer (1959)* | Pre | Y |
| ***62*** | Malaysian Rain Forest | *Harrison (1962)* | Pre | N |
| ***63*** | Tropical Seas, epipelagic zone | *Parin (1970)* | Pre | Y |
| ***64*** | Nearshore marine 1 | *Simenstad et al. (1978)* | Pre | N |
| ***65*** | Nearshore marine 1 (M) | *Simenstad et al. (1978)* | Pre | Y |
| ***66*** | Nearshore marine 2 | *Simenstad et al. (1978)* | Pre | N |
| ***67*** | Nearshore marine 2 (M) | *Simenstad et al. (1978)* | Pre | Y |

Table B52 continued: Food Web data as collected by Briand and Cohen and used in this dissertation (Briand 1983, Briand and Cohen 1987). The original references for the 69 food webs may be found in (Briand 1983, Briand and Cohen 1987).

| | **Name** *(M = modified to include detritus links)* | **Original Reference** *as listed in (Briand 1983)and (Briand and Cohen 1987)* | **Pre or Post 1993** | **Detritus (Y/N)** |
|---|---|---|---|---|
| ***68*** | Mississipi River Mudflats | *Carlson (1968)* | Pre | N |
| ***69*** | Mississipi River Mudflats (M) | *Carlson (1968)* | Pre | Y |

Table B53: Food web data for those food webs collected on or after 1993, extracted from the datasets of Borrett and Dunne Table B44 and Table B45 respectively. The numbering in the first column on the left corresponds to the numbering in Table B44 and Table B45.

| | **Name** | **Original Reference** | **Detritus (Y/N)** | **Cannibalistic Interactions** | **Actors (N)** |
|---|---|---|---|---|---|
| **B11** | Bothnian Bay | *Sandberg et al. (2000)* | N | 3 | *12* |
| **B12** | Bothnian Sea | *Sandberg et al. (2000)* | N | 3 | *12* |
| **B14** | Sundarban Mangrove (virgin) | *Ray (2008)* | Y | 0 | *14* |
| **B15** | Sundarban Mangrove (reclaimed) | *Ray (2008)* | Y | 0 | *14* |
| **B24** | Northern Benguela Upwelling | *Heymans and Baird (2000)* | N | 4 | *24* |
| **B25** | Swartkops Estuary | *Scharler and Baird (2005)* | Y | 5 | *25* |
| **B26** | Sunday Estuary | *Scharler and Baird (2005)* | Y | 4 | *25* |
| **B27** | Kromme Estuary | *Scharler and Baird (2005)* | Y | 5 | *25* |
| **B28** | Okefenokee Swamp | *Whipple and Patten (1993)* | Y | 0 | *26* |
| **B29** | Neuse Estuary (early summer 1997) | *Baird et al. (2004b)* | N | 3 | *30* |
| **B30** | Neuse Estuary (late summer 1997) | *Baird et al. (2004b)* | N | 2 | *30* |
| **B31** | Neuse Estuary (early summer 1998) | *Baird et al. (2004b)* | N | 1 | *30* |
| **B32** | Neuse Estuary (late summer 1998) | *Baird et al. (2004b)* | N | 2 | *30* |
| **B33** | Gulf of Maine | *Link et al. (2008)* | Y | 19 | *31* |
| **B34** | Georges Bank | *Link et al. (2008)* | Y | 19 | *31* |
| **B35** | Middle Atlantic Bight | *Link et al. (2008)* | Y | 21 | *32* |
| **B36** | Narragansett Bay | *Monaco and Ulanowicz (1997)* | Y | 2 | *32* |
| **B37** | Southern New England Bight | *Link et al. (2008)* | Y | 19 | *33* |
| **B39** | Mondego Estuary (Zostera sp. Meadows) | *Patricio and Marques (2006)* | Y | 8 | *43* |
| **B40** | St. Marks Seagrass, site 1 (Jan.) | *Baird et al. (1998)* | Y | 3 | *51* |

Table B53 continued: Food web data for those food webs collected on or after 1993, extracted from the datasets of Borrett and Dunne Table B44 and Table B45 respectively. The numbering in the first column on the left corresponds to the numbering in Table B44 and Table B45.

| | **Name** | **Original Reference** | **Detritus (Y/N)** | **Cannibalistic Interactions** | **Actors (N)** |
|---|---|---|---|---|---|
| **B41** | St. Marks Seagrass, site 1 (Feb.) | *Baird et al. (1998)* | Y | 3 | *51* |
| **B42** | St. Marks Seagrass, site 2 (Jan.) | *Baird et al. (1998)* | Y | 3 | *51* |
| **B43** | St. Marks Seagrass, site 2 (Feb.) | *Baird et al. (1998)* | Y | 3 | *51* |
| **B44** | St. Marks Seagrass, site 3 (Jan.) | *Baird et al. (1998)* | Y | 3 | *51* |
| **B45** | St. Marks Seagrass, site 4 (Feb.) | *Baird et al. (1998)* | Y | 3 | *51* |
| **B46** | Sylt-RomoBight | *Baird et al. (2004a)* | N | 0 | *59* |
| **B47** | Graminoids (wet) | *Ulanowicz et al. (2000)* | Y | 5 | *66* |
| **B48** | Graminoids (dry) | *Ulanowicz et al. (2000)* | Y | 5 | *66* |
| **B49** | Cypress (wet) | *Ulanowicz et al. (1997)* | Y | 0 | *68* |
| **B50** | Cypress (dry) | *Ulanowicz et al. (1997)* | Y | 0 | *68* |
| **B51** | Lake Oneida (pre-ZM) | *Miehls et al. (2009a)* | Y | 8 | *74* |
| **B52** | Lake Oneida (post-ZM) | *Miehls et al. (2009a)* | Y | 8 | *76* |
| **B53** | Bay of Quinte (pre-ZM) | *Miehls et al. (2009b)* | Y | 14 | *74* |
| **B54** | Bay of Quinte (post-ZM) | *Miehls et al. (2009b)* | Y | 15 | *80* |
| **B55** | Mangroves (wet) | *Ulanowicz et al. (1999)* | N | 0 | *94* |
| **B56** | Mangroves (dry) | *Ulanowicz et al. (1999)* | N | 0 | *94* |
| **B57** | Florida Bay (wet) | *Ulanowicz et al. (1999)* | Y | 0 | *125* |
| **B58** | Florida Bay (dry) | *Ulanowicz et al. (1999)* | Y | 0 | *125* |
| **D2** | St. Martin Island | *Goldwasser and Roughgarden 1993* | Y | 21 | *42* |
| **D3** | El Verde Rainforest | *Waide and Reagan 1996* | Y | 25 | *155* |
| **D4** | UK Grassland | *Martinez et al. 1999* | N | 25 | *61* |

Table B53 continued: Food web data for those food webs collected on or after 1993, extracted from the datasets of Borrett and Dunne Table B44 and Table B45 respectively. The numbering in the first column on the left corresponds to the numbering in Table B44 and Table B45.

| | **Name** | **Original Reference** | **Detritus (Y/N)** | **Cannibalistic Interactions** | **Actors (N)** |
|---|---|---|---|---|---|
| **D5** | Scotch Broom | *Memmott et al. 2000* | N | 4 | *85* |
| **D8** | Little Rock Lake | *Martinez et al. 1999* | N | 19 | *92* |
| **D9** | Canton Creek | *Townsend et al. 1998* | Y | 2 | *102* |
| **D10** | Stony Stream | *Townsend et al. 1998* | Y | 0 | *109* |
| **D12** | St. Marks Estuary | *Christian and Luczkovich 1999* | Y | 8 | *48* |
| **D14** | Ythan Estuary 1996 | *Huxham et al. 1996* | N | 0 | *124* |
| **D15** | Benguela | *Yodzis 1998* | N | 2 | *29* |
| **D16** | Caribbean Reef Small | *Opitz 1996* | Y | 4 | *50* |
| **D17** | NE US Shelf | *Link 2002* | Y | 4 | *79* |

# APPENDIX C

# ECO-INDUSTRIAL PARKS: INFORMATION

Table C54: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the 'eco' and/or 'industrial' themes; *Proposed*: 'green' practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | ABLE Project | Pre-operational | | | | | (Gibbs and Deutz 2007) |
| | AES Thames EIP | Exists? | x | x | | | (Chertow 2000, Hardy 2001, Chertow 2002, Daddona 2011) |
| | Alameda County EIP | Proposed | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Alberta By-Product Synergy Project | Exists | x | x | | | (Fons and Young 2006) |
| | Alberta's Industrial Heartland Project | Exists | x | x | | | (Wall 2003, Heeres, Vermeulen et al. 2004, Cote and Wallner 2006, Fons and Young 2006, Marwah 2008) |
| | Anaco Anacostia Ecogarden Project | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | An Son Village *(IBS)* | Proposed | x | x | | | (Hardy 2001, Hedlund 2003) |
| | AvestaPolarit | Pre-operational | | | | | (Gibbs and Deutz 2007) |
| | Avtex Redevelopment Project | Proposed | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Barceloneta, Puerto Rico | Exists | x | x | | ? | (Chertow, Ashton et al. 2008) |
| | Bassett Creek Valley EIP | Proposed | | | | | (Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| **Name** | | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | BCSD-NSR, National Industrial Symbiosis Programme | Pre-operational | | | | | (Gibbs and Deutz 2007) |
| | Berks County EIP | Proposed | | | | | (Short , Rotkin, Lubeck et al. 2004) |
| | Berrybank Farm IBS | Exists | | | | | |
| | Brownsville EIP | Attempted | | | | | (Short , Martin, Weitz et al. 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | Buffalo Forge EIP | Proposed 2001 | | | | | (Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007) |
| | Burnside EIP | Exists | | | | Poor | (Short , 1996, Rotkin, Lubeck et al. 2004, Cote and Wallner 2006) |
| | Cabazon *(RRP)* | Exists | | | | | (Short , 1996, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007, 2010, Burrows, Arnold et al. 2011) |
| | Cape Charles Sustainable Technologies Park | Exists/Failed | | | | | (Cote and Cohen-Rosenthal 1998, EPA 2000, Mitchell 2003, Kerr 2008) |
| | Cataño, Puerto Rico | Exists | x | x | | | (Aristizabal, Gerst et al. 2005) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Chattanooga SMART Park | Propsed | | | | | (Cote and Cohen-Rosenthal 1998, Kazemersky and Winters 1999) |
| | Cheney EIP | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Choctow EIP | Proposed | x | x | | | (Carr 1998) |
| | Civano Industrial Eco-Park | Attempted | | | | | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007, October 1996) |
| | Clark Special Economic Zone | Proposed | x | x | | | (Hardy 2001, Chertow 2002) |
| | Closed Project | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Coffee Creek Centre | Proposed | | | | | (Short , Saikku 2006, Gibbs and Deutz 2007) |
| | Computer and Electronics Disposition EIP | Proposed | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Connecticut Newsprint | Not EIP | x | x | | | (Hardy 2001) |
| | Copper Industry Web | Not EIP? | | | | | (Hardy 2001) |
| | Cowpens EIP | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Crewe Green Business Park | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Dagenham Sustainable IP | Pre-operational | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Dallas EIP | Pre-operational | | | | | (Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Debert EIP | Exists, adding | | | | | (Cote 2010) |
| | Devens EIP | Exists | x | x | | | (Hollander and Lowitt 2000, Hardy 2001, Saikku 2006, Gibbs and Deutz 2007) |
| | Dyfi EIP | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | East Bay EIP | Proposed | | | | | (1997-1998) |
| | East Shore EIP *(RRP)* | Proposed | | | | | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004) |
| | EATS Community Matrix | | x | x | | | (Hardy 2001) |
| | Ecotech | Pre-operational | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Emscher Park | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Energy & Research Park | Proposed | | | | | |
| | Enterprise South EIP (Volunteer Site) | Proposed | | | | | (Short , 1996, Rotkin, Lubeck et al. 2004, Saikku 2006) |
| | Fairfield EIP | Exists | | | | | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | Franklin County EIP | Attempted | | | | | (Short , Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|
| | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| Fort McMurray EIP | Proposed | | | | | (Marwah 2008) |
| Fushan Farm *(IBS)* | Exists? | x | x | | | (Chengchun 1994, Hardy 2001) |
| GERIPA *(IBS)* | Proposed | x | x | | | (Ometto, Ramos et al. 2007) |
| Gladstone, Australia | Exists | x | x | | | Van Beers 2007 |
| Green Institute Eco-Industrial Park | Exists | | | | | (Short , 1996, Cote and Cohen-Rosenthal 1998, Mitchell 2003, Rotkin, Lubeck et al. 2004) |
| Green Park | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Green Triangle | Proposed | x | x | | | (Hardy 2001) |
| Guayama, Puerto Rico | Exists | x | x | | | (Chertow and Lombardi 2005, Chertow, Ashton et al. 2008) |
| Guangxi Guitang Group | Exists | x | x | | | (Hardy 2001, Zhu and Cote 2004, Chertow 2007, Zhu, Lowe et al. 2007) |
| Gulf Coast By Product Synergy Project | Exists | x | x | | | (Gibbs and Deutz 2007) |
| Harjavalta Industrial Area | Exists | x | x | | | (Saikku 2006) |
| Hartberg Okopark | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Herning-Ikast IP | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Hinton Light/Innovista EIP | Proposed 2005 | | | | | (2005, Solutions 2005, Fons and Young 2006, Kerr 2008, Marwah 2008) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Humber Industrial Symbiosis Project | Exists | | | | | (Gibbs and Deutz 2007) |
| | Hyder Enterprise Zone | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Intervale Food Center (formerly Riverside Eco-Park) IBS | Proposed 1999, Pre-opertational | | | | | (Short , 1996, Mitchell 2003, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | Jyvaskyla, Finland | Exists | | | | | (Korhonen and Wihersaari 1999) |
| | Kalundborg | Exists | x | x | x | Limited water | (Hardy 2001, Mitchell 2003) (Jacobsen 2006) |
| | Kaizer Meadows Eco-Business Park | Proposed | | | | | (Cote 2010) |
| | Kwinana, Australia | Exists | x | x | | | (van Beers, Corder et al. 2007) |
| | Kymi EIP | | | | | | (Sokka, Pakarinen et al. 2011) |
| | Kytakyushu, Japan (RRP) | Exists | | | | | (Cote 2010) |
| | Landskrona Industrial Symbiosis Programme *(EIP)* | Exists, Adding | x | x | | | (Mirata and Emtairah 2005) |
| | Lima Technology Center | Exists | | x | | | (2000) |
| | Lloydminster EIP | Proposed | | | | | (Majumdar 2001, Fons and Young 2006) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| **Name** | | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Londonderry EIP | Pre-operational | x | x | | | (Cote and Cohen-Rosenthal 1998, Hardy 2001, Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007) |
| | London Remade Eco-Industrial Sites | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Lower Mississippi Corridor | Proposed | x | x | x | | (Singh, Lou et al. 2007) |
| | Maplewood Project | Proposed | | | | | (von Hausen, Casavant et al. 2004) |
| | Menomonee Valley | Proposed | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Monfort Boys Town IBS | Exists | x | x | | | (Klee 1999, Chertow 2000, Hardy 2001, 2011) |
| | Mongstad EIP | Proposed | x | x | x? | | (Zhang, Stromman et al. 2008) |
| | Montagna-Energie Valle di Non | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Monterey Resource Recovery Park | Exists | x | | | | (2011) |
| | Nanhai EIP | Proposed | | | | | (Chen, Li et al. 2008) |
| | Nanning Sugar | Exists | x | x | | | (Yang and Feng 2008) |
| | NIA | | | | | | (Bain, Shenoy et al. 2010) |
| | NW Louisiana Commerce Center | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Oulu Ecopark | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Ontario East Wood Centre and EIP | Proposed | | | | | (Cote 2010) |
| | Parc Industriel Plaine de l’Ain (PIPA) | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Ecosite du Pays de Thau | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Pearson eco-business zone | Exists, adding | | | | | (Cote 2010) |
| | Phillips Eco-enterprise Centre | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Plattsburgh EIP | Attempted | | | | Poor | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | Pomacle Bazancourt’s biorefinery | Exists | x | x | | | (Debref 2012) |
| | Port of Cape Charles Sustainable Technologies Industrial Park | Exists | | | | Poor | (Short , 1996, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | PV Symbiosis Proposition | Proposed | x | x | | | (Pearce 2008) |
| | Quzhou EIP | Proposed | x | | | | (Chen, Li et al. 2008) |
| | Rantasalmi EIP | Proposed | | | | | (Saikku 2006) |
| | Raymond Green EIP | Attempted | | | | | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
| | Red Hills EcoPlex | Pre-operational | x | x | | | (Hardy 2001, Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|
| | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| Renova Resource Recovery Park | Proposed | x | x | | | (Abuyuan, Hawken et al. 1999, Chertow 2002, Saikku 2006, Gibbs and Deutz 2007) |
| Righead Sustainable Industrial Estate | Pre-operational | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| River City Park | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Riverside EIP | Exists | | | | | (1996, Cote and Cohen-Rosenthal 1998) |
| Ross EIP | Exists, adding | | | | | (Cote 2010) |
| Rotterdam Harbour Industrial Ecosystems Programme | Proposed | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Saint Peter IBS | Attempted | | | | | (Mitchell 2003, Saikku 2006, Gibbs and Deutz 2007) |
| Sarnia, Ontario | Exists | | | | | (Cote and Wallner 2006) |
| The Scotia Investments EIP | Exists | | | | | (Cote 2009) |
| Selkirk EIP | Attempted | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| Seshasayee Paper and Board Ltd.: Agro-industrial Eco-complex | Exists | x | x | | | (Erkman and Ramaswamy 2000) |
| Shady Side Eco-Business Park | Attempted | | | | | (1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the 'eco' and/or 'industrial' themes; *Proposed*: 'green' practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

|  | **Name** | **Status** | **Information Type Available** |  |  |  | **Source** |
|---|---|---|---|---|---|---|---|
|  |  |  | **Companies** | **Links** | **Exchanges** | **Flow** |  |
|  | Skagit County Environmental Industrial Park | Attempted |  |  |  |  | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
|  | Sphere EcoIndustrie d'Alsace | Exists |  |  |  |  | (Saikku 2006, Gibbs and Deutz 2007) |
|  | Springfield | Proposed |  |  |  |  | (Saikku 2006, Gibbs and Deutz 2007) |
|  | Spruce Grove | Proposed |  |  |  |  | (Marwah 2008) |
|  | Stockholm, Environmental Science Park | Proposed |  |  |  |  | (Saikku 2006, Gibbs and Deutz 2007) |
|  | Stoneyfield Londonderry EIP | Proposed | x | x |  |  | (1996, Hardy 2001) |
|  | Styria Recycling Network | Exists | x | x |  |  | (Schwarz and Steininger 1997, Saikku 2006, Gibbs and Deutz 2007) |
|  | Sustainable Growth Park | Proposed |  |  |  |  | (Saikku 2006, Gibbs and Deutz 2007) |
|  | TaigaNova EIP | Proposed |  |  |  |  | (Marwah 2008, Cote 2010) |
|  | Trenton Eco-Industrial Complex | Attempted |  |  |  |  | (Short , 1996, Cote and Cohen-Rosenthal 1998, Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007) |
|  | Triangle J Council of Governments Regional IS Project | Inactive | x |  |  |  | (Kincaid 1999, Kincaid and Overcash 2001, Mitchell 2003, Cote and Wallner 2006, Saikku 2006, Gibbs and Deutz 2007, Boyer 2012) |

Table C54 continued: *Attempted*: range from those that failed in the planning stages to those that are fully operational but have abandoned the ‘eco’ and/or ‘industrial’ themes; *Proposed*: ‘green’ practices being developed in existing industrial parks, new EIPs under construction and/or recruiting tenants ; *Pre-operational*: ; *Exists*: currently (as up to date as found) functioning eco-industrial parks.

| | **Name** | **Status** | **Information Type Available** | | | | **Source** |
|---|---|---|---|---|---|---|---|
| | | | **Companies** | **Links** | **Exchanges** | **Flow** | |
| | Tunweni Brewery *(IBS)* | Exists | x | x | | | (Hardy 2001, 2011) |
| | Turin Environmental Park | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Uimaharju Forest Industry Park | Exists | x | x | | | (Korhonen and Snakin 2005) |
| | Ulsan Industrial Park (*EIP)* | Exists, Adding | x | x | | | (Park, Rene et al. 2008) |
| | UPM Kymi pulp and paper mill | Exists | x | x | | Some | (Pakarinen, Mattila et al. 2010) |
| | ValuePark ® | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Volunteer Site | Attempted | | | | | (Rotkin, Lubeck et al. 2004, Saikku 2006, Gibbs and Deutz 2007, October 1996) |
| | Vreten | Exists | | | | | (Saikku 2006, Gibbs and Deutz 2007) |
| | Wallingford EIP | Proposed | x | x | | | (Hardy 2001, Chertow 2002) |
| | Zaozhuang EIP | Proposed | x | x | | | (Chen, Li et al. 2008) |

# APPENDIX D

# ECO-INDUSTRIAL PARKS: DATA

Table D55: 48 EIPs with results for applied structural metrics.

| | | **Name** (IBS- integrated bio-systems, EIP- eco-industrial park, RRP- resource recovery park) | **Location** | **References** |
|---|---|---|---|---|
| ***1*** | ***failed*** | AES Thames EIP | Montville, CT | *(Reap 2009)* |
| ***2*** | ***exists*** | An Son Village | Vietnam | *(Hedlund and Bui Xuan 2000)* |
| ***3*** | ***exists*** | Barceloneta | Puerto Rico | *(Chertow, Ashton et al. 2008)* |
| ***4*** | ***failed*** | Brownsville EIP | Brownsville, TX | *(Martin, Weitz, Cushman et al. 1996)* |
| ***5*** | ***exists*** | Burnside EIP | Nova Scotia, Canada | *(Cote 2009)* |
| ***6*** | ***proposed*** | Clark Special Economic Zone | Philippines | *(Reap 2009)* |
| ***7*** | ***proposed*** | Connecticut Newsprint | Bridgeport, Connecticut | *(Reap 2009)* |
| ***8*** | ***exists*** | Copper Industry Web | N/A | *(Frosch, Clark, Crawford 1997)* |
| ***9*** | ***exists*** | Devens EIP | Ayer, Massachusetts | *(Reap 2009)* |
| ***10*** | ***exists?*** | Fushan Farms (IBS) | Zhuhai, China | *(Reap 2009)* |
| ***11*** | ***proposed*** | GERIPA (IBS) | Brazil | *(Ometto et al 2007)*<br>*(Reap 2009)* |
| ***12*** | ***exists*** | Gladstone (2005) | Gladstone, Australia | *(Corder 2008)*<br>*(Reap 2009)* |
| ***13*** | ***proposed*** | Gladstone (with potential links 2008) | Gladstone, Australia | *(Corder 2008)*<br>*(Reap 2009)* |
| ***14*** | ***proposed*** | The Green Triangle | Boston, Massachussetts | *(Reap 2009)* |
| ***15*** | ***exists*** | Guayama | Barrio Jobos in Guayama, Puerto Rico | *(Chertow, Ashton et al. 2008) (Reap 2009)* |
| ***16*** | ***exists*** | Guitang Sugarcane EIP Project | Guitang, China | *(Chertow 2007)*<br>*(Mathews and Tan 2011) (Reap 2009)* |
| ***17*** | ***exists*** | Harjavalta Industrial Area | Harjavalta, Finland | *(Saikku 2006)* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | | **Name** (IBS- integrated bio-systems, EIP- eco-industrial park, RRP- resource recovery park) | **Location** | **References** |
|---|---|---|---|---|
| ***18*** | ***exists*** | Humber Industrial Symbiosis Project | Scunthorpe, North Lincolnshire, England | *(Saikku 2006)* |
| ***19*** | ***exists*** | Jyvaskyla | Jyvaskyla, Finland | *(Saikku 2006)* |
| ***20*** | ***exists*** | Kalundborg EIP | Kalundborg, Denmark | *(Saikku 2006)*<br>*(Reap 2009)*<br>*(Jacobsen 2006)*<br>*(Mathews and Tan 2011)* |
| ***21*** | ***exists*** | Kawasaki | Japan | *(Mathews and Tan 2011) (Hashimoto, Fujita, Geng, Nagasawa 2010)* |
| ***22*** | ***exists*** | Kwinana | Australia | *(Mathews and Tan 2011) (van Beers et al 2005) (Corder 2008)* |
| ***23*** | ***?*** | Kymi EIP | Kymenlaakso, Finland | *(Sokka, Pakarinen et al. 2011)* |
| ***24*** | ***exists*** | Kytakyushu RRP | Kytakyushu, Japan | *(Cote 2010)* |
| ***25*** | ***exists*** | Landskrona | Landskrona, Sweden | *(Reap 2009)*<br>*(Roelse 2010)* |
| ***26*** | ***proposed*** | Lower Mississippi Corridor | Mississippi | *(Reap 2009)* |
| ***27*** | ***exists*** | Lubei Industrial Park | China | *(Mathews and Tan 2011)* |
| ***28*** | ***exists*** | Monfort Boys Town (IBS) | Suva, Fiji | *(Reap 2009)* |
| ***29*** | ***proposed*** | Mongstad EIP | Mongstad, Norway | *(Reap 2009)* |
| ***30*** | ***exists*** | Nanning Sugar Company | China | *(Reap 2009)* |
| ***31*** | ***?*** | NIA-KIADB | | *(Bain, Shenoy et al. 2010)* |
| ***32*** | ***exists*** | Pingdingshan Coal Mining Group | Pingdingshan, China | *(Mathews and Tan 2011)* |
| ***33*** | ***exists*** | Pomacle-Bazancourt | France | *(Debref 2012)(Chauvet 2012)* |
| ***34*** | ***proposed*** | PV Symbiosis Prop | | *(Reap 2009)* |
| ***35*** | ***proposed*** | Red Hills EcoPlex | Red Hills, Choctaw County, Mississippi | *(Reap 2009)* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | | **Name** (IBS- integrated bio-systems, EIP- eco-industrial park, RRP- resource recovery park) | **Location** | **References** |
|---|---|---|---|---|
| ***36*** | ***proposed*** | Renova (RRP) | Arecibo, Puerto Rico | *(Abuyuan et al. 1999)* |
| ***37*** | ***exists*** | Scotia Investments | Nova Scotia, Canada | *(Cote 2009)* |
| ***38*** | ***exists*** | Seshasayee Paper and Board Ltd.: Agro Industrial Eco-complex | India | *(Reap 2009)* |
| ***39*** | ***proposed*** | Stoneyfield Londonderry EIP | Londonderry, New Hampshire | *(Reap 2009)* |
| ***40*** | ***exists*** | Styrian Recycling Network | Styria, Austria | *(Roelse 2010)* |
| ***41*** | ***exists*** | Suzhou Eco-Industrial Park | Singapore/China | *(Mathews and Tan 2011)* |
| ***42*** | ***exists*** | Tianjin Economic Development Area | Tianjin, China | *(Mathews and Tan 2011) (Shi 2009)* |
| ***43*** | ***inactive*** | Triangle J EIP | North Carolina, USA | *(Kincaid 1999)* |
| ***44*** | ***exists*** | Tunweni Brewery (IBS) | Tsumeb, Namibia | *(Reap 2009)* |
| ***45*** | ***exists*** | Uimaharju Forest Industry Park | Uimaharju, Finland | *(Korhonen 2005) (Reap 2009)* |
| ***46*** | ***exists*** | Ulsan Industrial Park | Ulsan, South Korea | *(Behera 2012) (Reap 2009) (Mathews and Tan 2011)* |
| ***47*** | ***exists*** | UPM Kymi pulp and paper mill | Kuusankoski, South-Eastern Finland | *(Pakarinen, Mattila et al. 2010)* |
| ***48*** | ***?*** | Wallingford Eco-Industrial Park | Wallingford, Connecticut | *(Reap 2009)* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | **Actors (N)** | **Links (L)** | **Predator** | **Prey** | **Connectance with cannibalism ($C = L/N^2$)** | **Connectance without cannibalism ($C = L/N(N-1)$)** | **Linkage Density ($L_D$)** |
|---|---|---|---|---|---|---|---|
| ***1*** | *20* | *51* | *19* | *17* | *0.128* | *0.134* | *2.55* |
| ***2*** | *6* | *5* | *5* | *2* | *0.139* | *0.167* | *0.83* |
| ***3*** | *15* | *46* | *13* | *12* | *0.204* | *0.219* | *3.07* |
| ***4*** | *21* | *30* | *17* | *13* | *0.068* | *0.071* | *1.43* |
| ***5*** | *7* | *9* | *5* | *7* | *0.184* | *0.214* | *1.29* |
| ***6*** | *8* | *15* | *6* | *8* | *0.234* | *0.268* | *1.88* |
| ***7*** | *8* | *7* | *6* | *3* | *0.109* | *0.125* | *0.88* |
| ***8*** | *23* | *25* | *13* | *14* | *0.047* | *0.049* | *1.09* |
| ***9*** | *8* | *25* | *7* | *8* | *0.391* | *0.446* | *3.13* |
| ***10*** | *6* | *8* | *6* | *4* | *0.222* | *0.267* | *1.33* |
| ***11*** | *9* | *16* | *9* | *7* | *0.198* | *0.222* | *1.78* |
| ***12*** | *6* | *12* | *6* | *5* | *0.333* | *0.400* | *2.00* |
| ***13*** | *17* | *25* | *14* | *9* | *0.087* | *0.092* | *1.47* |
| ***14*** | *8* | *8* | *8* | *4* | *0.125* | *0.143* | *1.00* |
| ***15*** | *14* | *21* | *13* | *7* | *0.107* | *0.115* | *1.50* |
| ***16*** | *8* | *16* | *8* | *8* | *0.250* | *0.286* | *2.00* |
| ***17*** | *27* | *51* | *24* | *19* | *0.070* | *0.073* | *1.89* |
| ***18*** | *8* | *14* | *7* | *7* | *0.219* | *0.250* | *1.75* |
| ***19*** | *11* | *17* | *10* | *8* | *0.140* | *0.155* | *1.55* |
| ***20*** | *15* | *16* | *13* | *10* | *0.071* | *0.076* | *1.07* |
| ***21*** | *23* | *40* | *18* | *14* | *0.076* | *0.079* | *1.74* |
| ***22*** | *9* | *17* | *7* | *8* | *0.210* | *0.236* | *1.89* |
| ***23*** | *9* | *11* | *7* | *7* | *0.136* | *0.153* | *1.22* |
| ***24*** | *11* | *20* | *10* | *8* | *0.165* | *0.182* | *1.82* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | **Actors (N)** | **Links (L)** | **Predator** | **Prey** | **Connectance with cannibalism ($C = L/N^2$)** | **Connectance without cannibalism ($C = L/N(N-1)$)** | **Linkage Density ($L_D$)** |
|---|---|---|---|---|---|---|---|
| ***25*** | *8* | *11* | *8* | *6* | *0.172* | *0.196* | *1.38* |
| ***26*** | *14* | *10* | *9* | *6* | *0.051* | *0.055* | *0.71* |
| ***27*** | *4* | *4* | *3* | *3* | *0.250* | *0.333* | *1.00* |
| ***28*** | *9* | *24* | *8* | *8* | *0.296* | *0.333* | *2.67* |
| ***29*** | *9* | *14* | *8* | *6* | *0.173* | *0.194* | *1.56* |
| ***30*** | *8* | *16* | *8* | *8* | *0.250* | *0.286* | *2.00* |
| ***31*** | *11* | *33* | *11* | *11* | *0.273* | *0.300* | *3.00* |
| ***32*** | *7* | *10* | *5* | *7* | *0.204* | *0.238* | *1.43* |
| ***33*** | *7* | *11* | *7* | *6* | *0.224* | *0.262* | *1.57* |
| ***34*** | *13* | *28* | *12* | *10* | *0.166* | *0.179* | *2.15* |
| ***35*** | *39* | *44* | *28* | *23* | *0.029* | *0.030* | *1.13* |
| ***36*** | *9* | *14* | *9* | *8* | *0.173* | *0.194* | *1.56* |
| ***37*** | *8* | *11* | *6* | *8* | *0.172* | *0.196* | *1.38* |
| ***38*** | *19* | *18* | *8* | *15* | *0.050* | *0.053* | *0.95* |
| ***39*** | *8* | *9* | *8* | *7* | *0.141* | *0.161* | *1.13* |
| ***40*** | *9* | *20* | *9* | *8* | *0.247* | *0.278* | *2.22* |
| ***41*** | *16* | *28* | *14* | *14* | *0.109* | *0.117* | *1.75* |
| ***42*** | *13* | *28* | *10* | *12* | *0.166* | *0.179* | *2.15* |
| ***43*** | *12* | *18* | *11* | *9* | *0.125* | *0.136* | *1.50* |
| ***44*** | *8* | *9* | *8* | *7* | *0.141* | *0.161* | *1.13* |
| ***45*** | *9* | *20* | *9* | *8* | *0.247* | *0.278* | *2.22* |
| ***46*** | *16* | *28* | *14* | *14* | *0.109* | *0.117* | *1.75* |
| ***47*** | *13* | *28* | *10* | *12* | *0.166* | *0.179* | *2.15* |
| ***48*** | *12* | *18* | *11* | *9* | *0.125* | *0.136* | *1.50* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | **Prey/Predator Ratio ($P_r$)** | **Vulnerability (V)** | **Generalization (G)** | **Cyclicity ($\lambda_{max}$)** |
|---|---|---|---|---|
| ***1*** | *0.895* | *3.00* | *2.00* | *3.338* |
| ***2*** | *0.400* | *2.50* | *2.68* | *0* |
| ***3*** | *0.923* | *3.83* | *1.00* | *3.118* |
| ***4*** | *0.765* | *2.31* | *3.54* | *1.732* |
| ***5*** | *1.40* | *1.29* | *1.76* | *1.272* |
| ***6*** | *1.33* | *1.88* | *1.80* | *1.928* |
| ***7*** | *0.500* | *2.33* | *2.50* | *0* |
| ***8*** | *1.08* | *1.79* | *1.17* | *0* |
| ***9*** | *1.14* | *3.13* | *1.92* | *3.874* |
| ***10*** | *0.667* | *2.00* | *3.57* | *1.618* |
| ***11*** | *0.778* | *2.29* | *1.33* | *1.702* |
| ***12*** | *0.833* | *2.40* | *1.78* | *2.000* |
| ***13*** | *0.643* | *2.78* | *2.00* | *2.209* |
| ***14*** | *0.500* | *2.00* | *1.79* | *1.000* |
| ***15*** | *0.538* | *3.00* | *1.00* | *1.618* |
| ***16*** | *1.00* | *2.00* | *1.62* | *1.877* |
| ***17*** | *0.792* | *2.68* | *2.00* | *2.588* |
| ***18*** | *1.00* | *2.00* | *2.13* | *1.817* |
| ***19*** | *0.800* | *2.13* | *2.00* | *3.000* |
| ***20*** | *0.769* | *1.60* | *1.70* | *1* |
| ***21*** | *0.778* | *2.86* | *1.23* | *1* |
| ***22*** | *1.14* | *2.13* | *2.22* | *0* |
| ***23*** | *1.00* | *1.57* | *2.43* | *1.000* |
| ***24*** | *0.800* | *2.50* | *1.57* | *1.554* |
| ***25*** | *0.750* | *1.83* | *2.00* | *1.221* |

Table D55 continued: 48 EIPs with results for applied structural metrics.

| | **Prey/Predator Ratio ($P_r$)** | **Vulnerability (V)** | **Generalization (G)** | **Cyclicity ($\lambda_{max}$)** |
|---|---|---|---|---|
| ***26*** | *0.667* | *1.67* | *1.38* | *1* |
| ***27*** | *1.00* | *1.33* | *1.11* | *0* |
| ***28*** | *1.00* | *3.00* | *1.33* | *3.696* |
| ***29*** | *0.750* | *2.33* | *3.00* | *1.000* |
| ***30*** | *1.00* | *2.00* | *1.75* | *1.325* |
| ***31*** | *1.00* | *3.00* | *2.00* | *3.392* |
| ***32*** | *1.40* | *1.43* | *3.00* | *1.570* |
| ***33*** | *0.857* | *1.83* | *2.00* | *1.618* |
| ***34*** | *0.833* | *2.80* | *1.57* | *1* |
| ***35*** | *0.821* | *1.91* | *2.33* | *1* |
| ***36*** | *0.889* | *1.75* | *1.57* | *1.732* |
| ***37*** | *1.33* | *1.38* | *1.56* | *1.664* |
| ***38*** | *1.88* | *1.20* | *1.83* | *0.000* |
| ***39*** | *0.875* | *1.29* | *2.25* | *1.174* |
| ***40*** | *0.889* | *2.50* | *1.13* | *2.148* |
| ***41*** | *1.00* | *2.00* | *2.22* | *2.419* |
| ***42*** | *1.20* | *2.33* | *2.00* | *2.081* |
| ***43*** | *0.82* | *2.00* | *2.80* | *1* |
| ***44*** | *0.875* | *1.29* | *1.64* | *1.174* |
| ***45*** | *0.889* | *2.50* | *1.13* | *2.148* |
| ***46*** | *1.00* | *2.00* | *2.22* | *2.419* |
| ***47*** | *1.20* | *2.33* | *2.00* | *2.081* |
| ***48*** | *0.818* | *2.00* | *2.80* | *1* |

Table D56: Ranking of all 48 EIPs in terms of the food web metrics cyclicity, linkage density, prey to predator ratio, generalization, and vulnerability.

| | **Name** (IBS- integrated bio-systems, EIP- eco-industrial park, RRP- resource recovery park) |
|---|---|
| ***1*** | AES Thames EIP |
| ***14*** | The Green Triangle |
| ***33*** | Pomacle-Bazancourt |
| ***36*** | Renova (RRP) |
| ***6*** | Clark Special Economic Zone |
| ***8*** | Copper Industry Web |
| ***24*** | Kytakyushu RRP |
| ***22*** | Kwinana |
| ***46*** | Ulsan Industrial Park |
| ***18*** | Humber Industrial Symbiosis Project |
| ***45*** | Uimaharju Forest Industry Park |
| ***47*** | UPM Kymi pulp and paper mill |
| ***5*** | Burnside EIP |
| ***17*** | Harjavalta Industrial Area |
| ***11*** | GERIPA (IBS) |
| ***21*** | Kawasaki |
| ***23*** | Kymi EIP |
| ***41*** | Suzhou Eco-Industrial Park |
| ***9*** | Devens EIP |
| ***16*** | Guitang Sugarcane EIP Project |
| ***42*** | Tianjin Economic Development Area |
| ***38*** | Seshasayee Paper and Board Ltd.: Agro Industrial Eco-complex |
| ***20*** | Kalundborg EIP |
| ***15*** | Guayama |

Table D56 continued: Ranking of all 48 EIPs in terms of the food web metrics cyclicity, linkage density, prey to predator ratio, generalization, and vulnerability.

| | **Name** (IBS- integrated bio-systems, EIP- eco-industrial park, RRP- resource recovery park) |
|---|---|
| ***37*** | Scotia Investments |
| ***29*** | Mongstad EIP |
| ***4*** | Brownsville EIP |
| ***3*** | Barceloneta |
| ***35*** | Red Hills EcoPlex |
| ***10*** | Fushan Farms (IBS) |
| ***30*** | Nanning Sugar Company |
| ***44*** | Tunweni Brewery (IBS) |
| ***39*** | Stoneyfield Londonderry EIP |
| ***26*** | Lower Mississippi Corridor |
| ***34*** | PV Symbiosis Prop |
| ***48*** | Wallingford Eco-Industrial Park |
| ***28*** | Monfort Boys Town (IBS) |
| ***40*** | Styrian Recycling Network |
| ***25*** | Landskrona |
| ***2*** | An Son Village |
| ***19*** | Jyvaskyla |
| ***31*** | NIA-KIADB |
| ***27*** | Lubei Industrial Park |
| ***13*** | Gladstone (with potential links 2008) |
| ***32*** | Pingdingshan Coal Mining Group |
| ***43*** | Triangle J EIP |
| ***12*** | Gladstone (2005) |
| ***7*** | Connecticut Newsprint |

# APPENDIX E

# ECO-INDUSTRIAL PARKS: STRUCTURAL FOOD WEB MATRICES

Table E57: Food web matrix [**F**] for AES Thames.

| | | | from | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Coal Power Plant | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Composting | *1* | *0* | *1* | *0* | *1* | *0* | *1* | *0* |
| | **3** | Craft Brewery | *1* | *1* | *0* | *1* | *1* | *1* | *1* | *1* |
| | **4** | High-grade cardboard pro. | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| | **5** | Hops and Barley Farm | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Low-grade cardboard pro. | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| | **7** | Sewage Treatment | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Waste Plastic Recycling | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* |

Table E53 Food web matrix [**F**] for An Son Village.

| | | | from | | |
|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** |
| *to* | **1** | Pig Farming | *0* | *1* | *0* |
| | **2** | Biodigestor | *1* | *0* | *0* |
| | **3** | Crop Farming | *0* | *1* | *0* |

Table E54 Food web matrix [**F**] for Barceloneta.

| | | | from | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| *to* | **1** | hay farm | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | wastewater treatment facility | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **3** | pharmaceutical firms | *0* | *0* | *0* | *1* | *1* | *0* | *0* |
| | **4** | cogeneration facility | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **5** | waste management firms | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **6** | paint manufacture | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **7** | energy recovery | *0* | *0* | *0* | *0* | *1* | *0* | *0* |

Table E55 Food web matrix [**F**] for Brownsville.

| | | | *from* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
| | **1** | Refinery | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Asphalt | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **3** | Tank Farm | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Stone | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Power Plant | *1* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Gypsum Wallboard | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Chemical Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **8** | Oil Recycling | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *0* | *0* |
| | **9** | Water Pretreatment | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Seafood Processing | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Plastic Recycler | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *1* | *0* |
| | **12** | Discrete Parts | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **13** | Ballasts | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **14** | Textile Company | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **15** | Auto Parts | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **16** | Solvent Recycling | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* |

Table E56 Food web matrix [**F**] for Burnside.

| | | | *from* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| | **1** | recovery | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **2** | repair | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **3** | recycling | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* |
| | **4** | rental | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* |
| | **5** | remanufacturing | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| *to* | **6** | reclamation | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* |
| | **7** | reuse/resale | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **8** | manufacturing | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | distribution | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **10** | retail | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | service | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E57 Food web matrix [**F**] for Clark Special Economic Zone.

| | | | *from* | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| | **1** | Airport | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Alternative Fuels | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Composting | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **4** | Electronics | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Golf Course | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **6** | Greenhouses | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Grey Water Processing | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *1* | *0* | *0* | *0* |
| | **8** | Housing | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Landscaping | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **10** | Metal Fabrication | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Oil Processing | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **12** | Old Power Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **13** | Plastics | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **14** | Power Plant | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **15** | Solvent Recovery | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *0* | *1* | *1* | *0* | *0* | *0* |
| | **16** | Textiles | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **17** | Tire Manufac. | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **18** | Tire Processing | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **19** | Tobacco | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **20** | Cosmetics | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E58 Food web matrix [**F**] for Connecticut Newsprint.

| | | | from | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** |
| | **1** | composting | *0* | *0* | *1* | *0* | *0* | *0* |
| | **2** | Construction | *0* | *0* | *1* | *0* | *0* | *0* |
| | **3** | Printing | *0* | *0* | *0* | *0* | *1* | *0* |
| *to* | **4** | publishing | *0* | *0* | *1* | *0* | *0* | *0* |
| | **5** | recycling facility | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | soil engineering | *0* | *0* | *1* | *0* | *0* | *0* |

Table E59 Food web matrix [**F**] for Copper Industry Web.

| | | | from | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| | **1** | agglomerators/brokers | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | scrap dealers (small) | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | scrap dealers (large) | *1* | *1* | *0* | *1* | *0* | *0* | *1* | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* |
| | **4** | dismantlers | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | incinerators | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | landfills | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **7** | waste reclaimers/disposers | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *0* | *1* | *0* | *0* | *0* |
| *to* | **8** | finishers | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **9** | manufacturers | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *0* | *0* | *0* |
| | **10** | foundries | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **11** | virgin metal suppliers | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **12** | alloyers | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *1* | *0* | *0* |
| | **13** | smelters | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *1* | *0* | *1* | *0* |
| | **14** | refiners | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **15** | other users | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* |

Table E60 Food web matrix [**F**] for Devens.

| | | | | | | | | | | | | | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** |
| | **1** | municipal waste | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Cain's Foods | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Parm-Eco | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Nestal | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Electronics | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Plastic Recycle | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Southern Container | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **8** | Solvent Recycle | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Composting | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *0* |
| | **10** | Parker-Hannifin | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **11** | Ryerson Tull | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **12** | Sunoco Products | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **13** | Comoco Graphics | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **14** | Elora Software | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **15** | Image Software | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **16** | Webvan | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **17** | Loaves and Fishes | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **18** | Golf Course | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **19** | Landscaping | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **20** | Greenways | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **21** | Markson-Rosenthal | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E61 Food web matrix [**F**] for Fushan Farms.

|  |  |  | from |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| *to* | **1** | Chicken farming | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **2** | Biogas Generator 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 |
|  | **3** | Biogas Generator 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
|  | **4** | Fodder Production | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
|  | **5** | Pig farming | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
|  | **6** | Fish farming | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | **7** | Fertilizer production | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E62 Food web matrix [**F**] for GERIPA.

|  |  |  | from |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Alcohol production | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
|  | **2** | Cattle breeding | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
|  | **3** | Cogeneration | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
|  | **4** | Farm product processing | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
|  | **5** | Sugarcane farming | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
|  | **6** | Yeast treatment | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **7** | Biodigestor | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **8** | Vegetable Farming | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

Table E63 Food web matrix [**F**] for Gladstone 2005.

|  |  |  | from |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Alumina refining | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
|  | **2** | Aluminum smelting | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **3** | Cement and lime production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | **4** | Coal power plant | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **5** | Sewage treatment | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  | **6** | Spent solvent collection | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **7** | Used tire collection | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
|  | **8** | Waste transfer and recycle | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E64 Food web matrix [**F**] for Gladstone 2008.

| | | | *from* | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** |
| *to* | **1** | Geocycle | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Old tire suppliers | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Cement Australia | *1* | *1* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Rio Tinto Yarwun Refinery | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Orica Chemicals | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Local Fertilizers | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7** | Yarwun STP | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **8** | Construction, road base, soil enhancement | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| **9** | pH Control | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **10** | Queensland Energy Resources | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **11** | Pozzolanic Enterprises | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **12** | NRG Power Station | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **13** | Central Qld Ports Authority | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **14** | Aggregate for local construction | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **15** | Biomass from local sawmills | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **16** | Boyne Smelters | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **17** | Queensland Alumina | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *1* | *0* | *0* |
| **18** | Gladstone Area Water Board | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **19** | Construction, environmental control, CO2 sequestering | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| **20** | South Trees STP | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **21** | Calliope River STP | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **22** | Transpacific Industries Waste transfer station | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| **23** | Road base | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E65 Food web matrix [**F**] for the Green Triangle.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Arboretum | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *0* |
| | **2** | Audubon Society | *0* | *0* | *1* | *1* | *1* | *0* | *1* | *0* |
| | **3** | Composting | *1* | *1* | *0* | *1* | *0* | *1* | *1* | *1* |
| | **4** | Equipment Facility | *1* | *1* | *1* | *0* | *0* | *0* | *1* | *1* |
| | **5** | Farmer's market | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Local hospitals / businesses | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Nursery / Garden Center | *1* | *0* | *1* | *1* | *0* | *1* | *0* | *0* |
| | **8** | Zoo | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *0* |

Table E66 Food web matrix [**F**] for Guayama.

| | | | *from* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** |
| *to* | **1** | waste water treatment | *0* | *1* | *0* | *0* | *0* | *0* |
| | **2** | pharmaceuticals production | *0* | *0* | *1* | *0* | *0* | *0* |
| | **3** | AES Cogeneration Plant | *1* | *1* | *0* | *1* | *0* | *0* |
| | **4** | Chevron Phillips Refinery | *0* | *0* | *1* | *0* | *0* | *0* |
| | **5** | Industrial Landfills | *0* | *0* | *1* | *0* | *0* | *0* |
| | **6** | road construction | *0* | *0* | *1* | *0* | *0* | *0* |

Table E67 Food web matrix [**F**] for Guitang Sugarcane EIP Project.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| *to* | **1** | agricultural eco-farm | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **2** | sugar refinery | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **3** | pulp plant | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **4** | alcohol plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | paper mill | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Alkali recovery | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | cement mill | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *1* |
| | **8** | fertilizer plant | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| | **9** | power plant | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E68 Food web matrix [**F**] for Harjavalta Industrial Area.

| | | | *from* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** |
| *to* | **1** | Porin Iampovoima Oy | *0* | *0* | *0* | *1* | *0* | *0* |
| | **2** | AGA | *1* | *0* | *0* | *0* | *0* | *0* |
| | **3** | OMG | *1* | *1* | *0* | *1* | *1* | *0* |
| | **4** | Harjavalta Copper Oy | *1* | *1* | *1* | *0* | *0* | *0* |
| | **5** | Kemiro Oyj, Kemira Grow How Oy | *1* | *0* | *0* | *1* | *0* | *0* |
| | **6** | The city of Harjavalta | *1* | *0* | *0* | *0* | *0* | *0* |

Table E69 Food web matrix [**F**] for Humber ISP.

| | | | *from* | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** |
| | **1** | refineries | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | chemical industry | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | CHP | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Water treatment chemicals | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | plaster board manufacturer | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Bio-Diesel Production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Protein Extraction | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Food and Fish Processing | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **9** | Interior Decoration Products | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Pet Food | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Gasifier | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* |
| | **12** | Wastewater Treatment | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **13** | Local Farms | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* |
| | **14** | Furniture Production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **15** | SMEs | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **16** | Steel Works | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **17** | Cement Manufacturing | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |

Table E70 Food web matrix [**F**] for Jyvaskyla.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Rauhalahti Power Plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Plywood Mill | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Boiler Plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Suburban households, services | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Households Services Industry | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Kangas Paper Mill | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Greenlandia Horticultural Centre | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **8** | Electricity Distribution | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E71 Food web matrix [**F**] for Kalundborg.

| | | | *from* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| *to* | **1** | Fertiliser Industry | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Gyproc | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Bioteknisk Jordrens Soilrem | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* |
| | **4** | ASNAES Power Station | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Statoil Refinery | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Lake Tisso | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Farms | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **8** | Cement Industry | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Re-use basin | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | fish farms | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Nobo Nordisk + Novozymes | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **12** | Municipality of Kalundborg | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **13** | Wastewater Treatement | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **14** | Greenhouse | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E72 Food web matrix [**F**] for Kawasaki.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Cement Plant (DC Cement) | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Integrated Steel Works (JFE Steel) | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **3** | Commercial/Industrial/Municipal waste collectors | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **4** | Dismantling & Recycling firms (FJE Environment) | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Stainless Steel Mill (NAS) | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Paper Mill (Corelex) | *0* | *1* | *1* | *0* | *0* | *0* | *1* | *0* |
| | **7** | Micro-Turbine power plant | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **8** | External eco-economic system | *1* | *1* | *0* | *1* | *1* | *1* | *0* | *0* |

Table E73 Food web matrix [**F**] for Kwinana.

*from*

| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | Alumina refinery | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **2** | Cement and lime production | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Chemical and fertilizer production | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **4** | Chemical production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Chlor Alkali Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| *to* | **6** | Coal mining | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Coal-fired power plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Co-generation plant (1) | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **9** | Co-generation plant (2) | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Composing facility | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Construction company | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **12** | Fertilizer production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **13** | Gas-fired power plant | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **14** | Industrial gas production (1) | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **15** | Industrial gas production (2) | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **16** | Inorganic chemical production | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| **17** | Nickel mining | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **18** | Nickel refining | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **19** | Oil refining | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| **20** | Pig iron production | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| **21** | Synthetic rutile production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **22** | Titanium dioxide production | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| **23** | Titanium mineral processing | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| **24** | Turf farm | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| **25** | Water supply / treatment | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **26** | Worm farm | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **27** | Zirconia powder producer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E74 Food web matrix [**F**] for Kymi.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| *to* | **1** | Chlorine Dioxide Plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Pulp and Paper Plant | *1* | *0* | *1* | *1* | *0* | *1* | *0* | *1* |
| | **3** | Power Plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Calcium Carbonate Plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Landfill | *1* | *1* | *1* | *1* | *0* | *0* | *0* | *0* |
| | **6** | Hydrogen Peroxide Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Local Energy Plant | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Municipal Wastewater Treatment Plant | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |

Table E75 Food web matrix [**F**] for Kytakyushu.

| | | | *from* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| *to* | **1** | Tire Recycling Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **2** | Aquaculture Greenhouse Hydroponic Farming | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **3** | Paper Mill | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **4** | Municipality | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Non-Ferrous Metal Smelter | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **6** | Energy Users | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **7** | Asphalt, Tarmacadam Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **8** | Pharmaceutical Industry | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **9** | Concrete Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **10** | Ethanol and Bio-Fuels Production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **11** | Resource Recovery facility | *1* | *0* | *1* | *1* | *1* | *1* | *0* | *1* | *0* | *1* | *1* |

Table E76 Food web matrix [**F**] for Landskrona.

| | | | *from* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| | **1** | District heater | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Lead battery recycling | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **3** | Local community | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Steel dust recycling | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Various industries | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **6** | Waste management | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Agricultural seed pro. | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **8** | Waste water treatment | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Car glass pro. | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* |
| | **10** | Glass fiber pro. | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Printing 1 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **12** | Printing 2 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **13** | Energy Production | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **14** | DAD | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **15** | Resin Production | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E77 Food web matrix [**F**] for Lower Mississippi Corridor.

| | | | *from* | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** |
| | **1** | Ammonia Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Ammonium nitrate | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Benefication Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | DME | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* |
| | **5** | Ethyl-benzene | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Formic acid | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* |
| | **7** | Granular triple super phosphate | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Graphite and Hydrogen | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Gypsum Production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Methanol plant | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Methylamines | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* |
| *to* | **12** | Mono and diammonium phosphate | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **13** | New acetic acid | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **14** | New styrene | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **15** | Nitric acid plant | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **16** | Phosphoric acid plant | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **17** | Power generation | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **18** | Propene and hydrogen | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **19** | Propylene plant | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **20** | Sulfuric acid production | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **21** | Syngas | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **22** | UAN plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **23** | Urea plant | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* |

Table E78 Food web matrix [**F**] for Lubei Industrial Park.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Sulphuric acid plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Salt refinery | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Cement Mill | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* |
| | **4** | Bromine plant | *1* | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* |
| *to* | **5** | Ion exchange membrane | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **6** | Aquaculture | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Turbo-generator | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **8** | Ammonium phosphate plant | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **9** | External eco-economic system | *0* | *1* | *1* | *1* | *1* | *1* | *0* | *1* | *0* |

Table E79 Food web matrix [**F**] for Monfort Boys Town.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Brewery | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Mushroom Cultivation | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Pig Farming | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **4** | Local Community | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| *to* | **5** | Anaerobic Bio-digester | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Supplemental Feed/Fertilizer Production | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *1* |
| | **7** | Vegetable Farming | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* |
| | **8** | Fish Aquaculture | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **9** | Algae Farming | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |

Table E80 Food web matrix [**F**] for Mongstad.

| | | | *from* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| | **1** | Air processing | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Aquaculture | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *1* | *0* |
| | **3** | CHP Plant | *1* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **4** | CO2 capture | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **5** | CO2 compression | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **6** | Coal gasification | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Hydrogen separation | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Methanol / DME Synthesis | *0* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Oil extraction | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Oil refinery | *0* | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **11** | Waste water treatment | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |

Table E81 Food web matrix [**F**] for Nanning Sugar Company.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | **1** | Sugarcane Farming | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **2** | Sugar Production | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Pulp Production | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* |
| *to* | **4** | Alcohol Production | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Construction Block Production | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Cement Production | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Compound Fertilizer Production | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **8** | Paper Production | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |

Table E82 Food web matrix [**F**] for NIA-KIADB.

| | | | from | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| *to* | **1** | Garment manufacturer | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **2** | Electrical Insulation Manufacturer | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **3** | Oil Extraction Facility | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **4** | Plywood manufacturer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **5** | Granite Polishing Facilities | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **6** | Food Processing Facility 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **7** | Paper Mills | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **8** | Food Processing Facility 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **9** | Sugar Cane Refinery and Distillery | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **10** | CO2 Bottling Facility | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | **11** | Distillery | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **12** | Alcohol Distributor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | **13** | Textile Mill | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **14** | Aromatic Chemical Processor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E83 Food web matrix [**F**] for Pingdingshan Coal Mining Group.

| | | | from | | | |
|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** |
| *to* | **1** | building materials plant | 0 | 1 | 0 | 0 |
| | **2** | coal processing | 0 | 0 | 0 | 0 |
| | **3** | chemical plant | 0 | 1 | 0 | 0 |
| | **4** | external eco-economic system | 1 | 0 | 1 | 0 |

Table E84 Food web matrix [**F**] for Pomacle-Bazancourt.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Sugar Refinery | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *1* |
| | **2** | Champtor | *1* | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *1* |
| | **3** | Cogeneration Project | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | A.R.D., BioAmber, Soliance | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *1* |
| *to* | **5** | BioDemo | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Procethol 2G | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Champagne Cereales/Blethanol | *1* | *1* | *0* | *1* | *0* | *1* | *0* | *0* | *1* |
| | **8** | Ecole Centrale Paris | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Cristanol | *1* | *1* | *0* | *1* | *0* | *0* | *1* | *0* | *0* |

Table E85 Food web matrix [**F**] for PV Symbiosis Prop.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Al production | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Cardboard production | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Greenhouses | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| | **4** | Muni. Recycle | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **5** | Mushroom cultivation | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* |
| | **6** | Packaging production | *1* | *1* | *0* | *1* | *0* | *0* | *1* | *0* | *0* |
| | **7** | PV production | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **8** | Semiconductor recycling | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **9** | Sheet glass pro. | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |

Table E86 Food web matrix [**F**] for Red Hills EcoPlex.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | **1** | Poultry Processing | *0* | *0* | *0* | *1* | *1* | *0* | *0* | *0* |
| | **2** | Feed Mill | *1* | *0* | *1* | *0* | *1* | *0* | *0* | *0* |
| | **3** | Hydroponic Greenhouse | *0* | *0* | *0* | *1* | *1* | *0* | *1* | *0* |
| *to* | **4** | CO2 Recovery | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **5** | Power Generation | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Farming | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *1* |
| | **7** | Aquaculture | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* |
| | **8** | Fiber Board Production | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |

Table E87 Food web matrix [**F**] for Renova.

| | | | *from* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| | **1** | Agriculture / Aquaculture | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| | **2** | Anaerobic Digester | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| | **3** | Animal Feed Production | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **4** | Compost | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **5** | Ethanol Manufacture | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| *to* | **6** | Living Machine | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| | **7** | Lumber Mill | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **8** | Misc. Services | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| | **9** | Paper Mill | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| | **10** | Pharmaceuticals | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **11** | Waste-to-energy | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |

Table E88 Food web matrix [**F**] for the Scotia Investments.

| | | | *from* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| | **1** | Minas Basin Pulp and Power | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| | **2** | CKF Inc. | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | **3** | Scotia Recycling Inc. | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| *to* | **4** | Users | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| | **5** | Maritime Paper Products | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **6** | Other sources of recycled cardboard | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **7** | Other sources of paper and cardboard | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E89 Food web matrix [**F**] for Seshasayee Paper and Board Ltd.

| | | | *from* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| | **1** | Sugar Plantation | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| | **2** | Sugar Production | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **3** | Alcohol Production | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| *to* | **4** | Paper Production | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **5** | Handcrafted Paper Production | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | **6** | Wastewater Treatment | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **7** | Methane Generation | 0 | 0 | 1 | 0 | 0 | 1 | 0 |

Table E90 Food web matrix [**F**] for Stoneyfield Londonderry.

| | | | | | | | | | | *from* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| | **1** | Municipal | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **2** | Cement manufacture | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **3** | Fertilizer manufacture | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **4** | Agriculture | *0* | *0* | *1* | *0* | *1* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Composting | *1* | *0* | *1* | *1* | *0* | *0* | *1* | *1* | *1* | *0* | *0* | *0* | *0* |
| | **6** | Insectary | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| *to* | **7** | Wastewater treatment | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *1* | *1* | *0* | *0* | *0* |
| | **8** | Food processing | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **9** | Power generation | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **10** | Industry | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **11** | Materials recovery | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* | *0* |
| | **12** | Greenhouses | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **13** | Aquaculture | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |

Table E91 Food web matrix [**F**] for Styrian Recycling Network.

*from*

| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** | **31** | **32** | **33** | **34** | **35** | **36** | **37** | **38** | **39** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | Paper Producing Industry 3 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **2** | Paper Producing Industry 4 | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **3** | Press Board Industry | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Stone and Ceramic Industry 2 | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Scrap Material Dealer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **6** | Region of Voitsberg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | Cement Plant 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **8** | Construction Materials Industry 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **9** | Cement Plant 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | Mining Company | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **11** | Power Plant 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **12** | Wastewater Treatment | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **13** | Construction Materials Industry 1 | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **14** | Power Plant 2 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **15** | Region of Graz | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **16** | Cement Plant 5 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **17** | Cement Plant 4 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **18** | Paper Producing Industry 1 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| **19** | Iron Scrap Dealer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **20** | Iron Manufacturing Industry | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **21** | Used Tires Dealer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **22** | Colour Industry | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **23** | Cement Plant 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **24** | Cement Plant 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **25** | Paper Producing Industry 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **26** | Waste Paper Dealer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **27** | Paper Producing Industry 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **28** | Plastic Industry | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **29** | Used Oil Dealer 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30** | Used Oil Dealer 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **31** | Used Oil Dealer 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **32** | Fuel Producers | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **33** | Agricultural Associations | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **34** | Stone and Ceramic Industry 1 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *1* | *1* | *1* |
| **35** | Paper Producing Industry 2 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **36** | Chemical Industry | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **37** | Textile Industry 1 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **38** | Textile Industry 2 | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **39** | Saw Mills | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table E92 Food web matrix [**F**] for Suzhou.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Silicon crystal manufacturing | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Integrated Circuit (IC) assembly and testing | *1* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Inferior goods dismantling and reloading | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Electronic chemicals (EC) manufacturing | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| *to* | **5** | Thin-film transistor liquid crystal display (TFT-LCD) manufacturing | *0* | *1* | *0* | *1* | *0* | *0* | *0* | *1* | *0* |
| | **6** | Computer, cell phone, TV, etc. | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **7** | Copper foil | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |
| | **8** | Polychlorinated biphenal (PCB) manufacturing | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* |
| | **9** | External eco-economic system | *0* | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |

Table E93 Food web matrix [**F**] for Tianjin.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | **1** | Battery manufacturer | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **2** | Metallurgical plant | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Enterprises and residents | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| *to* | **4** | Landscaping company | *0* | *0* | *1* | *0* | *1* | *1* | *1* | *0* |
| | **5** | Power and heat plants | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Alkali company | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Enzymes plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* |
| | **8** | External eco-economic system | *1* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |

Table E94 Food web matrix [**F**] for Triangle J.

| | | | *from* | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** |
| | **1** | Poultry Farm | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Dehydrated Food Manufacturer | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Cotton Ginner | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **4** | Compost Producer | *0* | *1* | *1* | *0* | *0* | *1* | *0* | *1* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **5** | Brewery | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Absorbent Manufacturer | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **7** | Municipal Lanfill | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **8** | Sawmill | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Stone Quarry | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **10** | Mobile Home Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **11** | Amino Acid Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **12** | Animal Feed Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **13** | Batter Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **14** | Concrete Companies | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **15** | Power Plants | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **16** | Municipal Water Treatement Plant | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *1* | *0* | *0* |
| | **17** | Pharmacutical Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **18** | Polyester Fiber Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **19** | Brick Manufacturer | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *1* | *0* | *1* | *0* |

Table E95 Food web matrix [**F**] for Tunweni Brewery.

| | | | *from* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | **1** | Brewery | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **2** | Substrate preparation | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **3** | Mushroom cultivation | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **4** | Pig farming | *1* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **5** | Feed manufacture | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Methane digester | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **7** | Algae cultivation | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* |
| | **8** | Aquaculture | *0* | *0* | *0* | *0* | *0* | *0* | *1* | *0* |

Table E96 Food web matrix [**F**] for Uimaharju Forest Industry Park.

| | | | *from* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| | **1** | Gas plant | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | **2** | Pulp Mill | *1* | *0* | *1* | *0* | *1* | *0* | *1* | *1* | *0* |
| | **3** | Sawmill | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **4** | Wastewater treatment | *0* | *1* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| *to* | **5** | CHP Plant | *0* | *1* | *1* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **6** | Ash treatment | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* |
| | **7** | Forest ecosystem | *0* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* |
| | **8** | Lake | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *0* |
| | **9** | Landfill | *1* | *1* | *1* | *1* | *1* | *1* | *0* | *0* | *0* |

Table E97 Food web matrix [**F**] for Ulsan Industrial Park.

| | | | *from* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
| | **1** | LS-NIKKO Corp. | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **2** | SK Chemical Corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | **3** | Hankuk Paper Co. | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **4** | Koentec Crop. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | **5** | KUMHO Petrochemical Corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **6** | Koreazinc | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **7** | O WWTF | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| *to* | **8** | SK Corp. | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **9** | S LANDFILL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **10** | Samsung Fine Chemical Corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **11** | SMWIF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **12** | Taeyoug industry corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **13** | TS Corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **14** | Ulsan Pacific | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **15** | Y WWTF | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| | **16** | SCR Tech Corp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

Table E98 Food web matrix [**F**] for UPM Kymi pulp and paper mill.

| | | | *from* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| *to* | **1** | Hydropower Plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **2** | Forest Ecosystem | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **3** | Calcium-carbonate Plant | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | **4** | Chlorine Dioxide Plant | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | **5** | Hydrogen Peroxide Plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **6** | Paper Mill | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **7** | Pulp Mill | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| | **8** | Landfill | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **9** | Municipal wastewater treatment plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | **10** | Wastewater treatment plant | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| | **11** | Water Purification Plant | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **12** | Energy Distributor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **13** | Power Plant | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |

Table E99 Food web matrix [**F**] for Wallingford.

| | | | *from* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *actor* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| *to* | **1** | Wallboard Facility | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **2** | Ash Processor | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **3** | Concrete Production | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | **4** | Power Plant | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **5** | Golf Course | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **6** | Stainless Steel Rolling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | **7** | Polymer Fabrication | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | **8** | Steel Rolling | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **9** | Specialty Wire Production | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| | **10** | Steel Mini-mill | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| | **11** | Gas Plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **12** | Municipal Waste to Energy | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |

# APPENDIX F

# INDUSTRIAL NETWORKS: FLOW-BASED FOOD WEB MATRICES

Table F100: Flow matrix [**T**] for the original water flow network in Albareto, Northern Italy (ORIGINAL system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | | | | | | | | | | | Exports | Dissipation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | 10 | 11 |
| Imports | *0* | *0* | *1.68E+03* | *0* | *3.48E+07* | *0* | *9.34E+04* | *3.41E+06* | *5.59E+05* | *0* | *0* | *0* |
| **1 Water Distribution System** | *0* | *0* | *1.46E+05* | *2.05E+03* | *2.98E+04* | *0* | *0* | *0* | *0* | *0* | *3.80E+05* | *0* |
| **2 Families and Commerce** | *0* | *0* | *0* | *0* | *0* | *9.30E+04* | *0* | *0* | *0* | *4.07E+05* | *0* | *1.12E+03* |
| **3 Public Services** | *0* | *0* | *0* | *0* | *0* | *1.65E+03* | *0* | *0* | *0* | *3.98E+02* | *0* | *0* |
| **4 Agriculture** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2.28E+06* | *2.15E+07* | *1.43E+07* |
| **5 Sewer system-treatment plant** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *9.46E+04* | *0* | *0* |
| **6 Wells** | *0* | *0* | *9.34E+04* | *0* | *1.00E+01* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **7 Waterbodies in** | *0* | *0* | *2.59E+05* | *0* | *3.15E+06* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **8 Springs** | *0* | *5.59E+05* | *0* | *0* | | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **9 Water bodies out** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2.79E+06* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table F101: Flow matrix [**T**] for the modified water flow network in Albareto, Northern Italy (MODIFIED system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | Exports 10 | Dissipation 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imports | *0* | *0* | *1.68E+03* | *0* | *3.48E+07* | *0* | *9.34E+04* | *3.32E+06* | *1.78E+05* | *0* | *0* | *0* |
| **1 Water Distribution System** | *0* | *0* | *1.46E+05* | *2.05E+03* | *2.98E+04* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **2 Families and Commerce** | *0* | *0* | *0* | *0* | *0* | *9.30E+04* | *0* | *0* | *0* | *4.07E+05* | *0* | *1.12E+03* |
| **3 Public Services** | *0* | *0* | *0* | *0* | *0* | *1.65E+03* | *0* | *0* | *0* | *3.98E+02* | *0* | *0* |
| **4 Agriculture** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2.28E+06* | *2.15E+07* | *1.43E+07* |
| **5 Sewer system-treatment plant** | *0* | *0* | *0* | *0* | *9.46E+04* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **6 Wells** | *0* | *0* | *9.34E+04* | *0* | *1.00E+01* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **7 Waterbodies in** | *0* | *0* | *2.59E+05* | *0* | *3.06E+06* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **8 Springs** | *0* | *1.78E+05* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **9 Water bodies out** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2.69E+06* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table F102: Flow matrix [**T**] for the original water flow network in Saramato, Northern Italy (ORIGINAL system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | | | | | | | | | | | | Exports | Dissipation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | 11 | 12 |
| Imports | *0* | *0* | *2.68E+03* | *0* | *1.66E+07* | *0* | *0* | *0* | *3.48E+06* | *8.44E+06* | *0* | *0* | *0* |
| **1 Water Distribution System** | *0* | *0* | *1.92E+05* | *5.90E+03* | *1.50E+03* | *0* | *6.11E+04* | *0* | *0* | *0* | *0* | *2.90E+04* | *0* |
| **2 Families and Commerce** | *0* | *0* | *0* | *0* | *0* | *1.85E+05* | *0* | *0* | *0* | *0* | *9.08E+03* | *0* | *1.15E+03* |
| **3 Public Services** | *0* | *0* | *0* | *0* | *0* | *5.90E+03* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **4 Agriculture** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *5.38E+06* | *1.44E+07* |
| **5 Sewer system-treatment plant** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2.41E+05* | *0* | *0* |
| **6 Industry** | *0* | *0* | *0* | *0* | *0* | *5.07E+04* | *0* | *0* | *0* | *0* | *1.56E+06* | *3.41E+03* | *1.40E+06* |
| **7 Aquaculture** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *5.50E+06* | *0* | *0* |
| **8 Wells** | *0* | *2.90E+05* | *0* | *0* | *2.78E+06* | *0* | *4.10E+05* | *0* | *0* | *0* | *0* | *0* | *0* |
| **9 Water bodies in** | *0* | *0* | *0* | *0* | *3.98E+05* | *0* | *2.54E+06* | *5.50E+06* | *0* | *0* | *0* | *0* | *0* |
| **10 Water bodies out** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *7.31E+06* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table F103: Flow matrix [**T**] for the modified water flow network in Saramato, Northern Italy (MODIFIED system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | Exports 11 | Dissipation 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imports | 0 | 0 | 2681 | 0 | 16620000 | 0 | 0 | 0 | 670300 | 5898000 | 0 | 0 | 0 |
| **1 Water Distribution System** | 0 | 0 | 192100 | 5900 | 1500 | 0 | 61060 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2 Families and Commerce** | 0 | 0 | 0 | 0 | 0 | 184600 | 0 | 0 | 0 | 0 | 9081 | 0 | 1149 |
| **3 Public Services** | 0 | 0 | 0 | 0 | 0 | 5900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4 Agriculture** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5376000 | 14420000 |
| **5 Sewer system-treatment plant** | 0 | 0 | 0 | 0 | 0 | 0 | 2540000 | 0 | 0 | 0 | 422800 | 0 | 0 |
| **6 Industry** | 0 | 0 | 0 | 0 | 0 | 50710 | 0 | 0 | 0 | 0 | 1560000 | 3411 | 1397000 |
| **7 Aquaculture** | 0 | 0 | 0 | 0 | 2778000 | 2722000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **8 Wells** | 0 | 260600 | 0 | 0 | 0 | 0 | 409700 | 0 | 0 | 0 | 0 | 0 | 0 |
| **9 Water bodies in** | 0 | 0 | 0 | 0 | 398300 | 0 | 0 | 5500000 | 0 | 0 | 0 | 0 | 0 |
| **10 Water bodies out** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1992000 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table F104: Flow matrix [**T**] for the original water flow network in Ravenna, Northern Italy (ORIGINAL system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | Exports 12 | Dissipation 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imports | *0* | *0* | *69840* | *0* | *461600000* | *54140000* | *0* | *367200000* | *0* | *10000000* | *0* | *0* | *0* | *0* |
| **1 Water Distribution System** | *0* | *0* | *11870000* | *417500* | *67870* | *40180* | *2097000* | *0* | *0* | *0* | *0* | *0* | *3737000* | *0* |
| **2 Families and Commerce** | *0* | *0* | *0* | *0* | *0* | *10350000* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *3062000* |
| **3 Public Services** | *0* | *0* | *0* | *0* | *0* | *417500* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **4 Agriculture** | *0* | *0* | *0* | *0* | *0* | *716200* | *0* | *0* | *0* | *0* | *0* | *22630000* | *16130000* | *451900000* |
| **5 Sewer system-treatment plant** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *39800000* | *0* | *46840000* |
| **6 Industry** | *0* | *0* | *0* | *0* | *0* | *20960000* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *189700* |
| **7 Power Plants** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *363500000* | *0* | *3672000* |
| **8 Potabilization Plant** | *0* | *18230000* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *2379000* | *0* |
| **9 Wells** | *0* | *0* | *3000000* | *0* | *7000000* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| **10 Water bodies in** | *0* | *0* | *0* | *0* | *22720000* | *0* | *19060000* | *0* | *20610000* | *0* | *0* | *0* | *0* | *27820000* |
| **11 Water bodies out** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *427500000* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |
| | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *0* |

Table F105: Flow matrix [**T**] for the modified water flow network in Ravenna, Northern Italy (MODIFIED system) as collected by Bodini and Bondavalli.(Bodini and Bondavalli 2002). Flows are measured in [$m^3$/yr].

| | 0 | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | Exports 12 | Dissipation 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imports | 0 | 0 | 69840 | 0 | 461600000 | 54140000 | 0 | 367200000 | 0 | 1 | 45320000 | 0 | 0 | 0 |
| **1 Water Distribution System** | 0 | 0 | 14880000 | 417500 | 67870 | 40180 | 2097000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2 Families and Commerce** | 0 | 0 | 0 | 0 | 0 | 10350000 | 0 | 0 | 0 | 0 | 0 | 1530000 | 0 | 3062000 |
| **3 Public Services** | 0 | 0 | 0 | 0 | 0 | 417500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4 Agriculture** | 0 | 0 | 0 | 0 | 0 | 716200 | 0 | 0 | 0 | 0 | 0 | 22630000 | 16130000 | 451900000 |
| **5 Sewer system-treatment plant** | 0 | 0 | 0 | 0 | 29730000 | 0 | 19060000 | 0 | 0 | 0 | 0 | 354600000 | 0 | 46840000 |
| **6 Industry** | 0 | 0 | 0 | 0 | 0 | 20960000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 189700 |
| **7 Power Plants** | 0 | 0 | 0 | 0 | 0 | 563500000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3672000 |
| **8 Potabilization Plant** | 0 | 17500000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **9 Wells** | 0 | 0 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10 Water bodies in** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17500000 | 0 | 0 | 0 | 0 | 27820000 |
| **11 Water bodies out** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 377880000 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# APPENDIX G

## ECO-INDUSTRIAL PARKS: COMBO EIPS

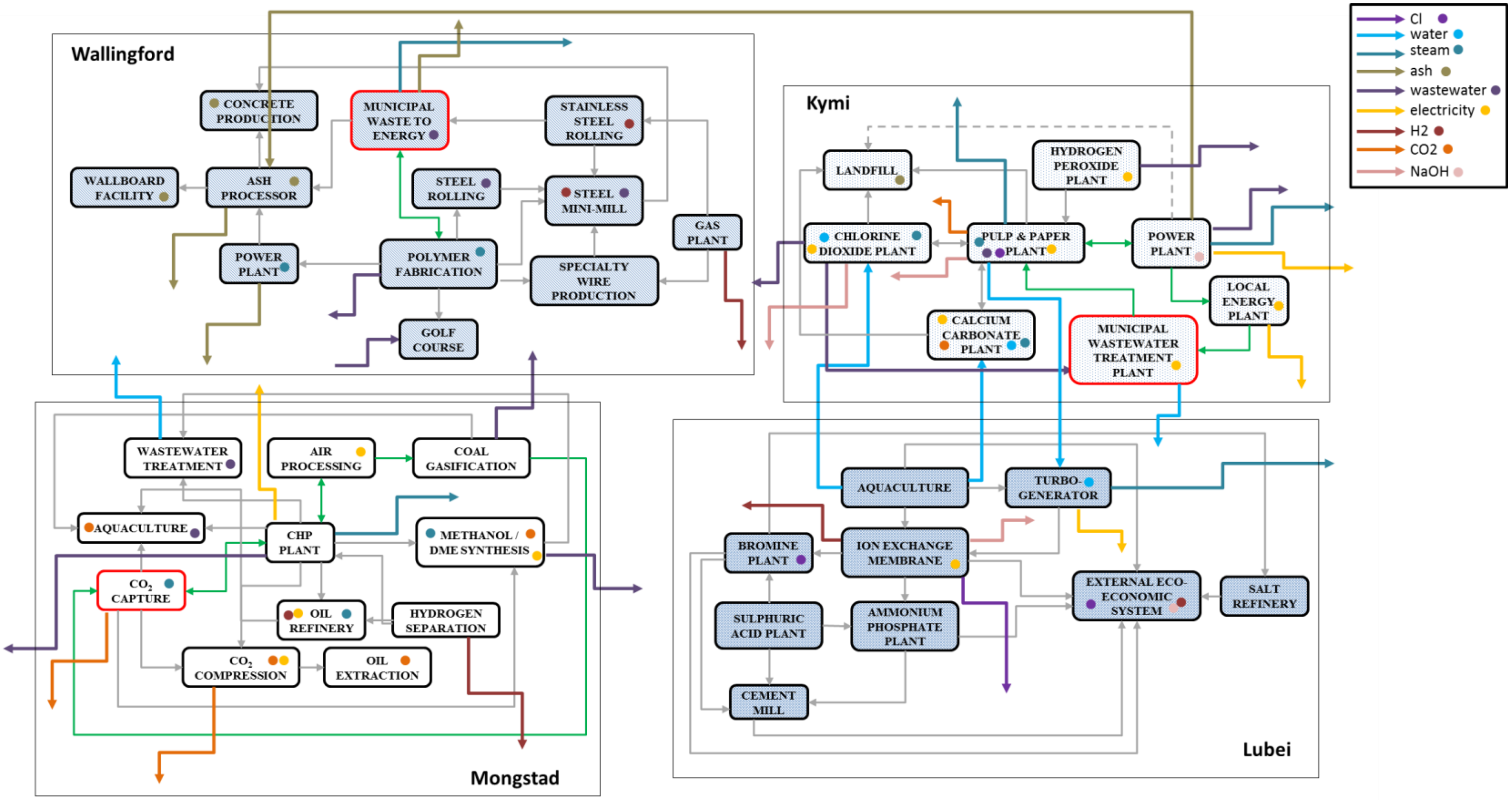


Figure G76: Combo 1EIP with Lubei, Mongstad, Wallingford, and Kymi

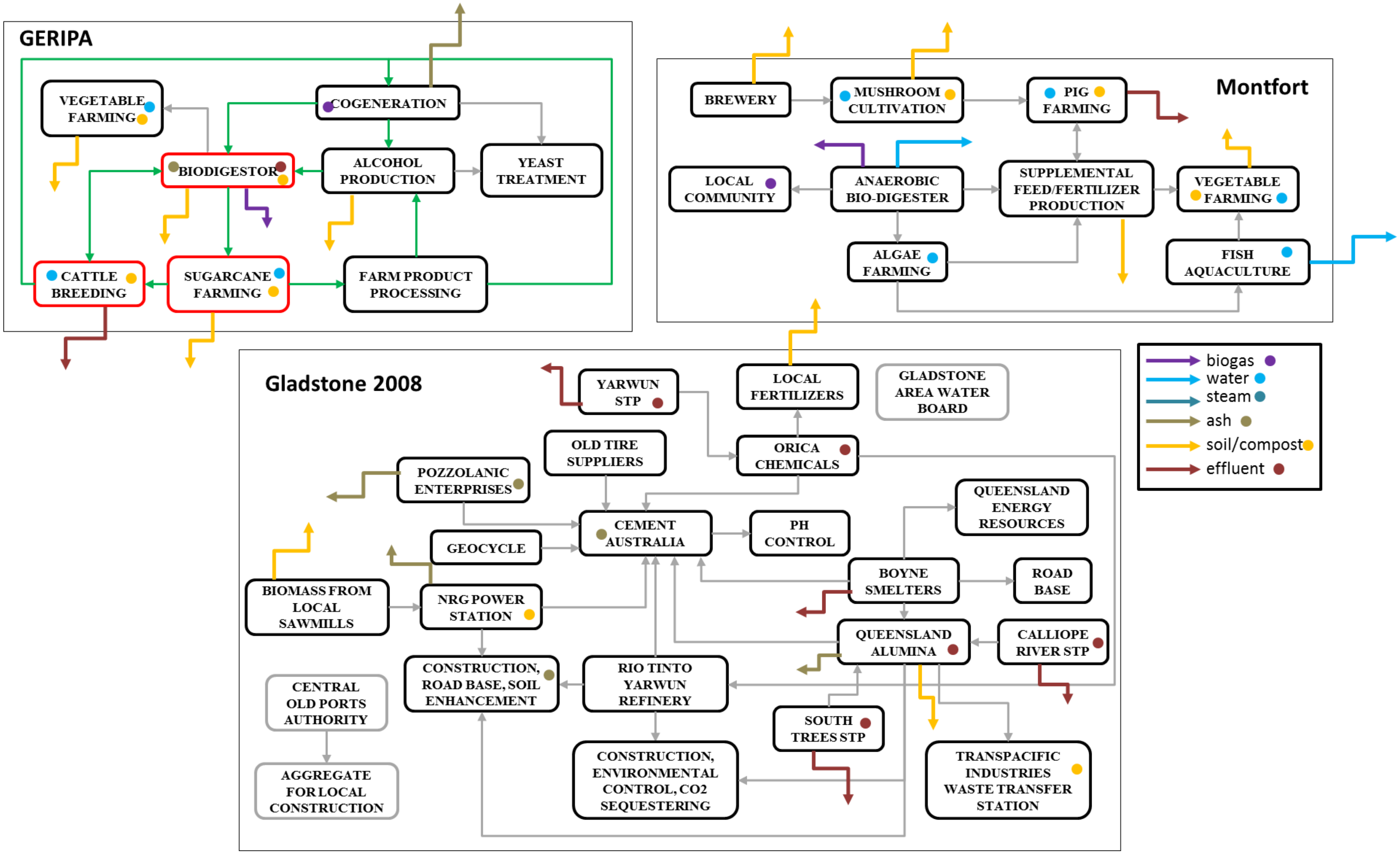


Figure G77: Combo2 EIP with GERIPA, Gladstone, and Montfort

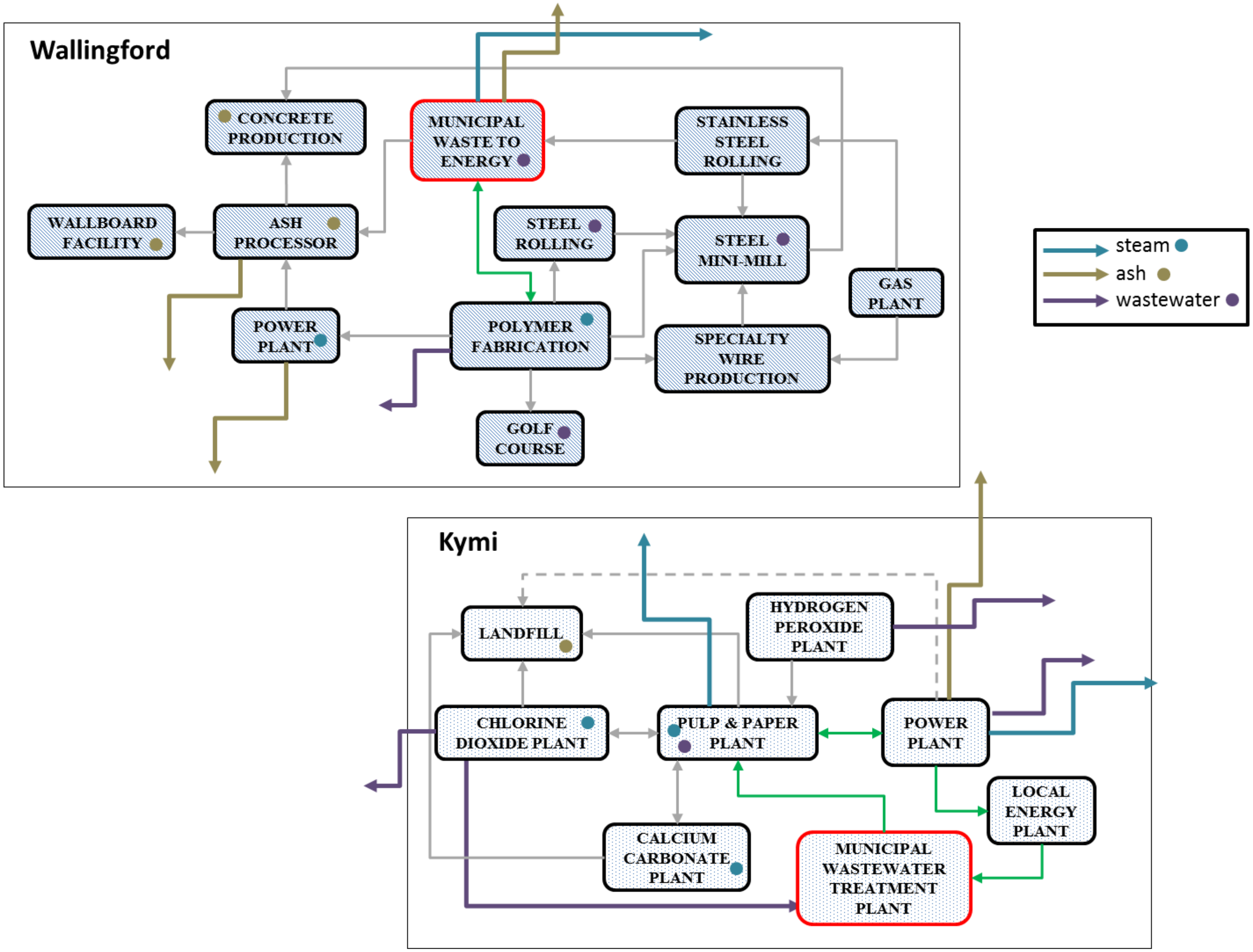


Figure G78: Combo 3 EIP with Kymi and Wallingford

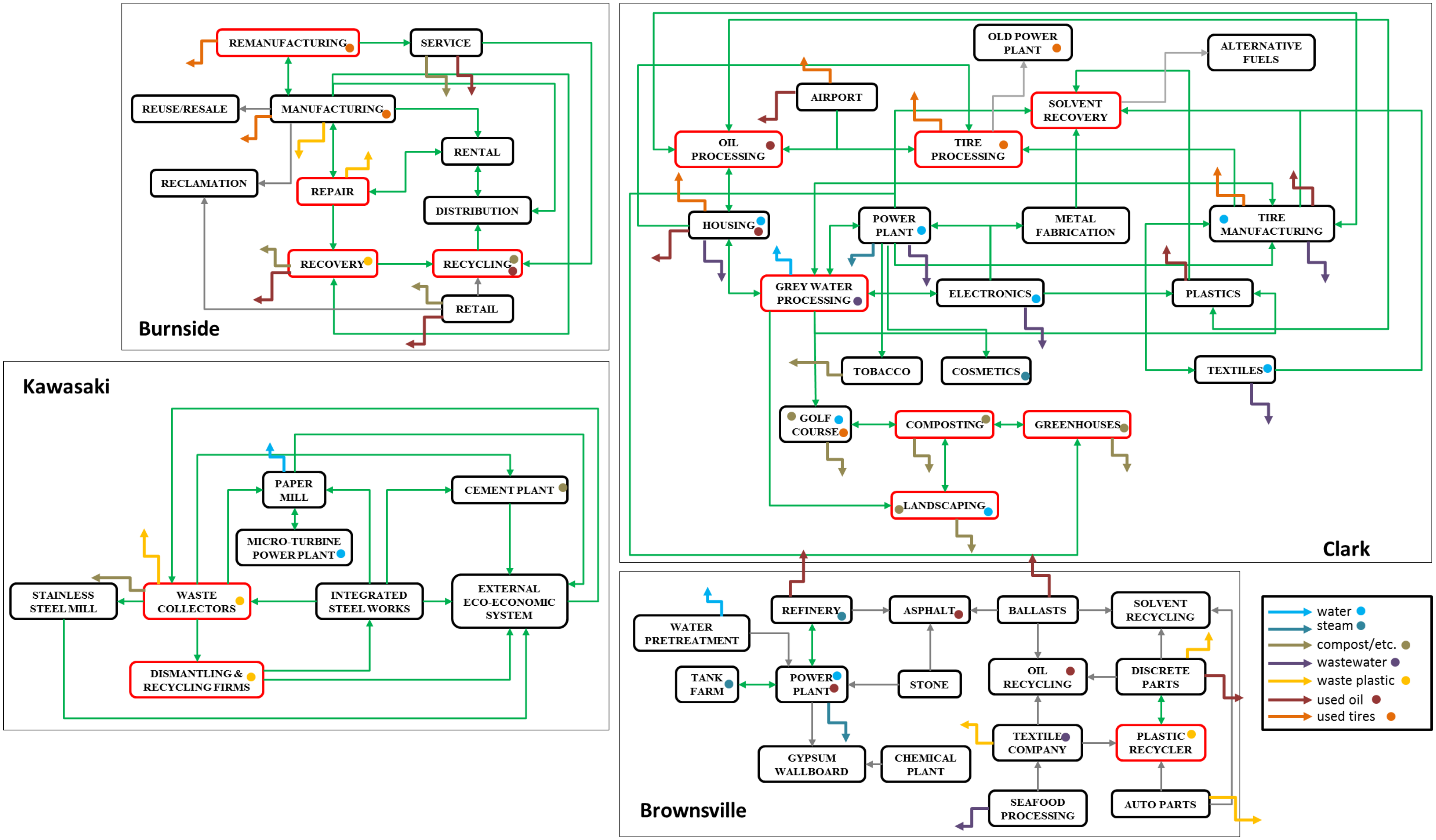


Figure G79: Combo 4 EIP with Brownsville EIP, Burnside EIP, Clark Special Economic Zone, and Kawasaki

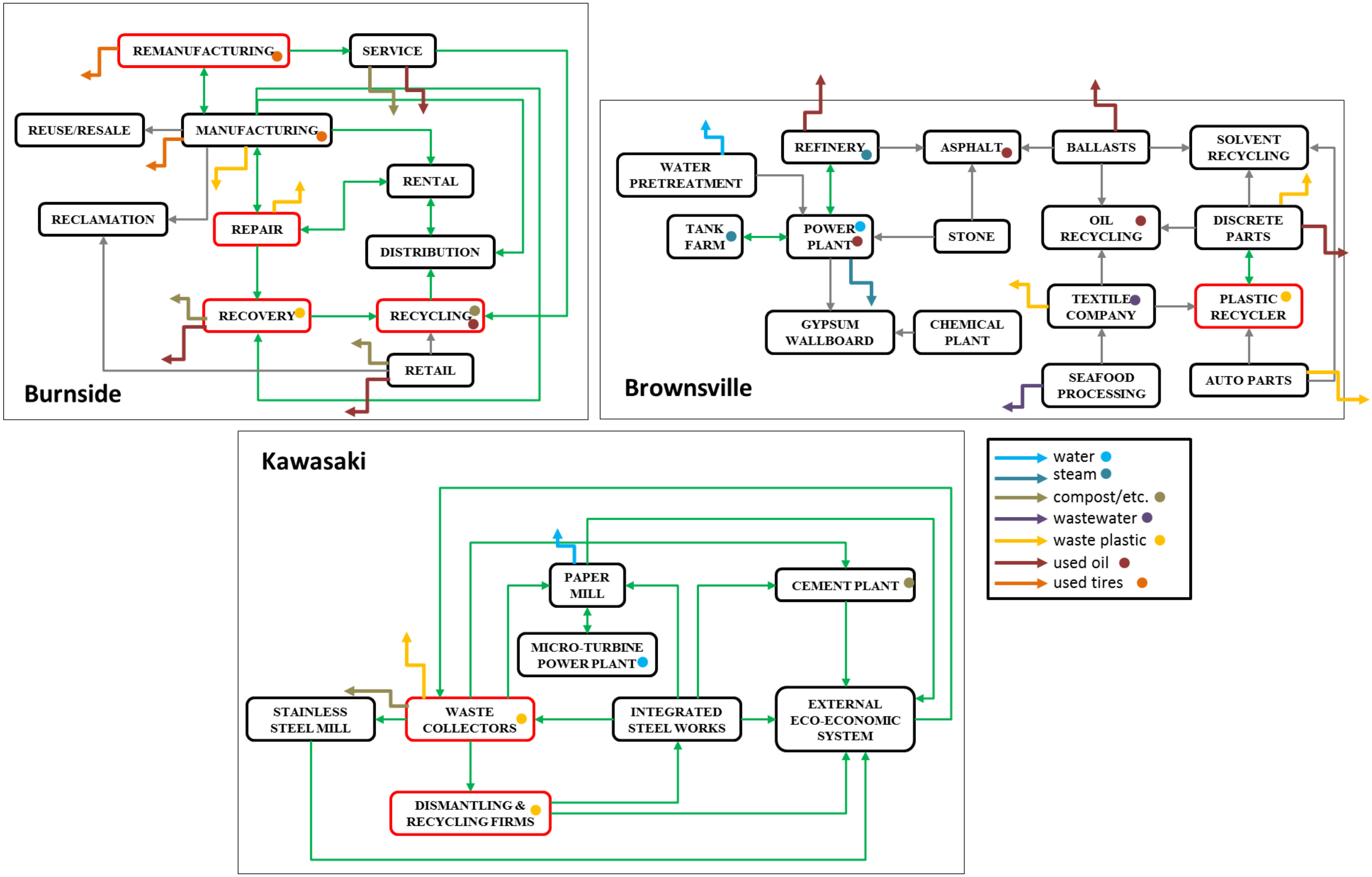


Figure G80: Combo 5 EIP with Brownsville EIP, Burnside EIP, and Kawasaki (i.e. no agriculture)

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# VITA

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